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PHOSPHATE REMOVAL BY ACTIVATED SLUDGE, AMENABILITY STUDIES AT CLEVELAND, OHIO

L. D. Lively, et al

Robert S. Kerr Water Research Center
Ada, Oklahoma

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AMENABILITY STUDIES AT CLEVELAND, OHIO

U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMINISTRATION
ROBERT S. KERR WATER RESEARCH CENTER
ADA, OKLAHOMA

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PHOSPHATE REMOVAL BY ACTIVATED SLUDGE

Amenability Studies at Cleveland, Ohio

by

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ABSTRACT

Phosphate removal by activated sludge was investigated in pilot- and plant-scale research conducted at the Cleveland, Ohio Easterly Pollution Control Center. These studies showed that the aeration tanks were averaging 25 percent removal of the orthophosphate in the tank influent. The following conditions were different from those found in the San Antonio Rilling Plant: (1) biochemical oxygen demand (BOD) and orthophosphate (as P) levels in the primary effluent (PE) were much lower, averaging 125 and 2.5 mg/l, respectively; (2) mixed liquor suspended solids (MLSS) concentrations were higher, ranging from 1,500 to 2,500 mg/l; (3) BOD loadings were lower, ranging from 0.20 to 0.35 lb/lb MLSS/day; and (4) aeration tank dissolved oxygen (DO) profiles were characteristic of the tapered aeration practiced. Mixed liquor aeration and operation of the final clarifiers were similar to those of the Rilling Plant.

Pilot investigations were made to determine the amenability of the waste and activated sludge to phosphate removal. A slight increase in removal was observed with increasing MLSS or oxygen-demanding substrate concentration. Ferric iron or aluminum salt addition caused high orthophosphate removals. Orthophosphate addition resulted in reduced removal efficiency. After an acclimation period of 18 to 42 hours, the sludge removed significant quantities of orthophosphate. Excluding the chemical addition studies, the maximum removal efficiency was 67 percent. The waste and sludge were concluded as only "moderately" amenable to phosphate removal.

A plant trial should be undertaken to optimize operating conditions essential for phosphate removal prior to final commitment of this facility as a biological phosphate removal demonstration site. This is recommended because of the "moderate" amenability attained in pilot studies and the marked differences in loading and operating parameters with the San Antonio Rilling Plant.

INTRODUCTION

This report describes investigations at the Easterly Pollution Control Center, Cleveland, Ohio, in a continuing research program concerned with the removal of phosphate from municipal sewage by the activated sludge process. Field research conducted at San Antonio, Texas, established that high removals of orthophosphate from the liquid to the mixed liquor solids were accomplished in the aeration tanks. The efficiency of the process was controlled by the operational parameters: aeration detention time, air supplied, mixed liquor suspended solids concentration, BOD load, phosphate load, rapid solid-liquid separation, and separate phosphorus disposal in the final clarifiers.

The purposes of the amenability studies conducted were:

1. To determine if biological phosphate uptake is feasible in municipalities of various geographical locations, populations served, and sewage characteristics by pilot and plant investigations.

2. To locate six or more activated sludge plants in various geographical regions to be used for demonstration of biological phosphate removal by operation in accordance with parameters identified at San Antonio.

3. To locate one activated sludge plant of suitable design and operational flexibility for use as a full-scale research plant to further specify, define, and optimize the biological phosphate removal process.

4. To verify on pilot scale that biological phosphate removal can be controlled by the parameters identified at San Antonio[1] and/or isolate and identify additional controlling parameters.

Aerated jugs of mixed liquor previously shown to simulate an aeration tank circumvent many of the limitations exerted by normal operational characteristics in activated sludge plants, such as control of aeration rate, sewage flow, suspended solids concentration, and phosphate and BOD loadings. Sludge solids and waste from various points in the secondary system may be conveniently studied. Detention

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[1]Priesing, C. P., et al., "Phosphate Removal by Activated Sludge--Pilot Research," Robert S. Kerr Water Research Center, Ada, Oklahoma. Presented October 11, 1967, New York WPCF Meeting.

time of the mixed liquor in the aerated jug system is rigidly controlled. For these reasons, the method was selected for testing the amenability of the waste and activated sludge to phosphate removal.

By deliberate variation of the operational parameters, the conditions for sludge response and maximum phosphate removal can be established. Amenability studies will indicate those waste and activated sludges most readily adaptable and, that, in conjunction with plant investigations, will aid in specifying operational levels, design changes, or time for sludge adaptability necessary to attain phosphate removal in the full-scale plant.

Experimental Procedures

Plant Analysis

The plant was studied to determine pertinent design and operational characteristics and performance. Plant records were examined for type and frequency of sewage flow, plant loading of BOD, suspended solids, and orthophosphate concentrations, analyses of chemical and physical parameters, and performance characteristics. Typical data are presented in Appendix II. Plant personnel were questioned about sampling practices, analytical procedures, anomalies of wastes being treated, and peculiarities of operational control. The schedules for wasting raw and activated sludges were determined. Disposal methods of waste activated sludge, primary sludge, digester supernatant, sludge thickener supernatant, drying bed underflow, and other waste streams were studied in anticipation of auxiliary, inhibitory, or latent effects on the phosphate removal process.

Tracer studies were conducted using Rhodamine WT dye in aeration tanks and final clarifiers to determine hydraulic characteristics such as detention, short circuiting, and degree of longitudinal mixing.

Grab samples were collected throughout the plant to determine the phosphate levels and degree of removal. These samples were analyzed for orthophosphate concentration and, occasionally, for total phosphate and total suspended solids (TSS). Chemically fixed samples were sent to the Robert S. Kerr Water Research Center at Ada, Oklahoma, for total phosphate and chemical oxygen demand (COD). The sample sources were: raw sewage, PE, return sludge (RS), aeration tank influent, aeration tank effluent, and final effluent. Occasionally, supernatant samples were taken from sludge thickeners. DO measurements were made throughout the plant in conjunction with the sampling program. When these studies indicated that phosphate was being removed, more detailed sampling on a slug-flow basis was undertaken to specify the magnitude of removal.

Aeration Jug Studies

Return sludge or mixed liquor from various points in the secondary system was mixed with primary effluent or raw sewage to obtain the desired range of suspended solids concentration. The mixtures were prepared in five-gallon polyethylene jugs for subsequent aeration.

A portable air compressor was used as the air supply. Air was delivered through a manifold containing individual needle valves and rotometers for each jug. Polyethylene tee fittings were used as diffusers. The air flow was maintained constant throughout the experiment, except where noted.

Dissolved oxygen content and temperature of the mixed liquor were monitored several times during each run.

Samples were withdrawn from the jugs usually at half-hour or hourly intervals. Preceding sample collection, approximately 200 ml of mixed liquor was siphoned through the Tygon withdrawal tube for purging and returned to the original jug. A volume of 100 ml was sufficient for orthophosphate determination, and 250 ml was taken when additional analyses were planned.

RESULTS AND DISCUSSIONS

Plant Characteristics

The Easterly Cleveland Sewage District reaches along Lake Erie from the mouth of the Cuyahoga River to East 185th Street and includes city and suburban areas which drain northward to the lakes. The population served is approximately 603,000.

The present activated sludge plant was designed to treat an average sewage flow of 123 million gallons per day (mgd). The existing plant was constructed in 1937 with the exception of the standby bar screens and grit chambers which were part of the original installation built in 1920-1922. The removal of TSS and BOD throughout the plant averages approximately 85 and 90 percent, respectively. The plant layout and flow sequence are shown in Figure 1.

Sewers in the Easterly Cleveland District are combined sanitary-storm sewers. Preliminary treatment facilities consist of comminutors, detritus tanks, and preaeration tanks to grind solids, remove grit, and flocculate oil and grease. Primary treatment facilities consist of 8 rectangular clarifiers, each 115' x 50' x 15' liquid depth. Sludge and scum are collected and pumped to the Southerly Cleveland Sewage Treatment Plant for processing and disposal.

Secondary treatment facilities incorporate the conventional activated sludge process. The aeration units consist of 16 double-pass, rectangular tanks built in four separate batteries of four tanks each. Each pass is 334 feet long by 27 feet wide by 15 feet liquid depth. The design flow is 123 mgd of primary effluent with 31 mgd of return sludge. The displacement time is five hours at design flow. Aerated channels transport primary effluent and return sludge to and take mixed liquor from the aeration tanks.

Three 40,000-cfm and two 25,000-cfm centrifugal multistage blowers provide process air. Air flow is controlled and metered to each aeration tank separately by cone control valves and Venturi meters. In each double-pass tank, air diffusers consist of 1,184 12" x 12" x 1" aluminum oxide plates having a permeability range of 30 to 60. The ratio of plate surface to tank liquid surface is approximately 1 to 10. The plates are positioned in two adjacent rows extending along one side wall to produce a spiral-roll flow pattern. At a spacing

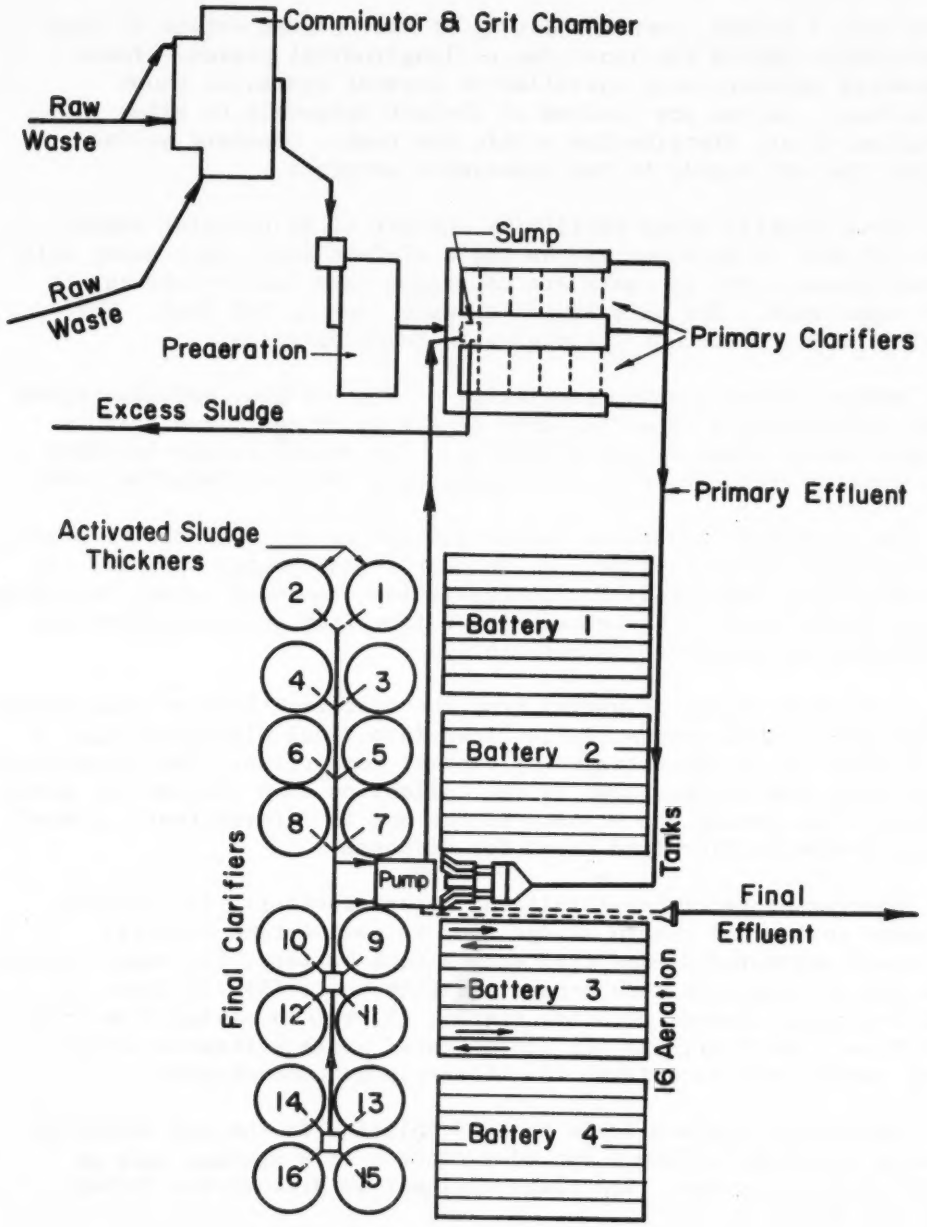

FIGURE 1 - PLANT LAYOUT SHEET, CLEVELAND, OHIO

of 64 feet 3 inches, rows consisting of nine plates extend 10 feet transversely beyond the inner row of longitudinal plates. These transverse aerators were installed to prevent hydraulic short circuiting. Valves are located at 25-foot intervals to allow variation of air distribution within the tank. Separate valves control the air supply to the transverse aerators.

Final clarification facilities consist of 16 circular tanks, each 112 feet in diameter and having a 12-foot side-water depth with center inlets. The 16 tanks are separated into four batteries of four tanks each. The weir length of each tank is 340 feet. The final clarifiers are not equipped with inlet baffling.

Return sludge pumping facilities consist of four variable speed pumps each having a capacity range of 4.7 to 10 mgd. Two standby pumps of equal capacity are available. The return sludge is mixed with primary effluent prior to introduction into the aeration tanks.

The secondary treatment facilities can be operated as one plant, as two 8-tank battery plants, or as four 4-tank battery plants. It is possible to completely isolate batteries from each other, including return sludge flow. The return sludge flow from each clarifier can be sampled and monitored independently.

Activated sludge is wasted from the discharge side of each return sludge pump. This excess sludge flows into Final Clarifiers Nos. 1 and 2 where it is concentrated by blanket compaction. The concentrated waste activated sludge flows to the collection sump (Figure 1), where it mixes with grease and primary sludge and is intermittently pumped to the Southerly Cleveland Plant for disposal.

Indicating-recording-totalizing meters monitor: (1) primary effluent inflow and return sludge flow to each 4-tank battery, (2) waste activated sludge from each 4-tank battery, (3) mixed liquor flow and air input to each 2-pass aeration tank, (4) air input to each 2-battery channel aeration system, (5) return sludge flow from each final clarifier, and (6) concentrated waste activated sludge being pumped from each final clarifier-sludge concentrator.

Facilities are available to feed chlorine to the raw sewage or primary clarifier influent for odor control at a maximum rate of 20,000 pounds per day. The plant effluent is disinfected during June and July.

Typical Plant Operation

Table 1 shows the significant secondary process operational data extracted from the Easterly Pollution Control Center Annual Report - 1966:

Table 1

Plant Operating Data

	Monthly Average		
	Max.	Min.	Avg.
Primary Effluent Flow (mgd)	127.6	103.8	117.7
Mixed Liquor Fow (mgd)	165.3	135.7	153.4
Return Sludge Flow (mgd)	38.2	31.9	35.6
% Return Sludge	35.0	27.8	30.2
Waste Activated Sludge (mgd)	0.52	0.33	0.42
Air Applied (cu. ft./gal.)	1.32	0.96	1.11

The primary effluent normally has a BOD of 125 mg/l and a suspended solids concentration of 100 mg/l. The final effluent contains about 20 mg/l of BOD and suspended solids.

Phosphate concentrations throughout the plant are routinely monitored by plant personnel. Monthly report sheets for April-December 1966 have been included in Appendix II. During this period, the average concentrations of total phosphate ($T\text{-}PO_4$) and dissolved phosphate were 18.5 mg/l and 9.5 mg/l, respectively. The removal of total and dissolved phosphate averaged 16 and 6.3 percent, respectively, during primary treatment. The corresponding removal efficiencies during secondary treatment were 33 and 15 percent.

Plant Monitoring

During the study period of April 18-28, 1967, plant operating data were collected. Due to the large number of treatment units, most of the survey data were collected on Battery No. 3 which includes aeration tanks and Final Clarifiers Nos. 9 through 12. Detailed plant operating data for this battery are given in Appendix III. Twenty-four hour charts, collected from the Battery No. 3 meters, monitored mixed liquor flow from each aeration tank, return sludge flow from each final clarifier, air flow to each aeration tank, and air provided for channel aeration. A summary of these data follows:

1. Hydraulic Loading

Dry weather primary effluent flow varied from a peak of 30 to 35 mgd from 12:00 Noon to 2:00 p.m. to a low of 18 to 21 mgd from 5:00 a.m. to 7:00 a.m. Rainfall on April 21-24 altered the diurnal

variation flow for these dates and caused peak flow rates of 40 to 50 mgd. Return sludge flow ranged from 9.5 to 10 mgd during peak flow conditions to 6 to 7 mgd during periods of low flow. The percent return sludge was normally 27 to 30 during dry weather flow, but dropped to a low of 19 during wet weather flows.

2. Dye Tracer Studies

Aeration Tanks - At 1:00 p.m. on April 19, two liters of 20 percent Rhodamine WT dye was added to the inlet of Aeration Tank No. 9 to determine its flow-through characteristics. Samples were collected from the 1/4, 1/2, 3/4, and end points of this tank at 15- to 60-minute intervals. Dye concentration in these samples was determined by means of a fluorometer. Effluent sampling discontinued at 6:00 p.m., accounting for 85 percent of the dye added.

The average mixed liquor flow rate through the 2 million-gallon aeration tank of 11.1 mgd resulted in a theoretical displacement time of 4.25 hours. Each two-pass aeration tank has a length-width ratio of 25:1. The average amount of air applied during the study was 4,800 cubic feet per minute or 0.6 cubic foot per gallon of mixed liquor.

Figure 2 is a graphical plot of dye concentration at the half and end points of the aeration tanks and a percent flow-through for the end point versus the time elapsed after dye addition. The mode, median, t_{10}, and t_{90} (10 and 90 percent flow-through times) are 3.5, 3.6, 2, and 6 hours, respectively. The dispersion index (t_{90}/t_{10}) is 3.0, and the modal detention time is equal to 82 percent of the theoretical displacement time. The Cleveland aeration tanks have essentially the same amount of longitudinal mixing and percent of plug flow as the aeration tanks of the Rilling Plant in San Antonio, Texas.[2]

Referring to Figure 2, 10 percent of the mixed liquor receives less than two hours of aeration and 30 percent less than three hours. Such flow-through characteristics have been found adequate to allow 80 percent phosphate removal.[1] Reducing the hydraulic loading would lengthen the average detention time and produce conditions more conducive to phosphate removal if other operating parameters can be simultaneously adjusted to satisfactory levels. The plant superintendent indicated that the plant is flexible enough to allow the reduction of flow to one of the four batteries for an extended period of time without creating undesirable effluent characteristics.

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[2]Priesing, C. P., et al., "Phosphate Removal by Activated Sludge--Plant Research," Robert S. Kerr Water Research Center, Ada, Oklahoma. Presented October 11, 1967, New York WPCF Meeting.

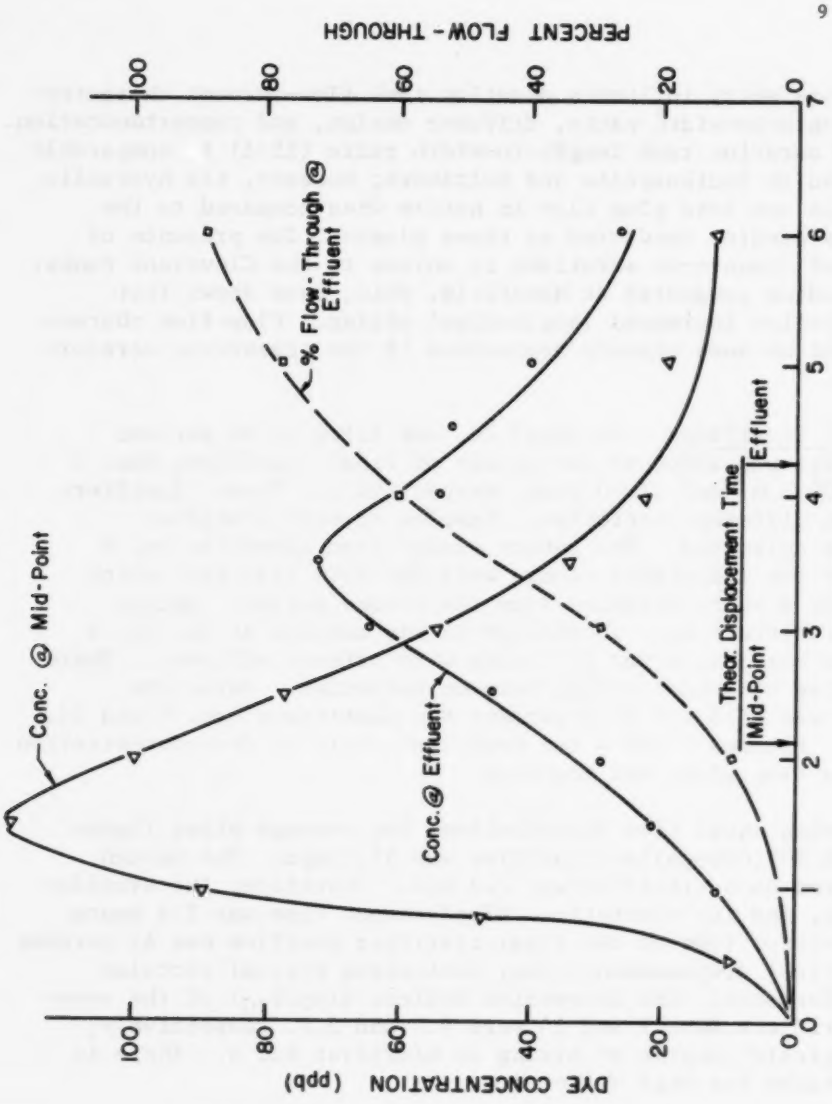

FIGURE 2 – DYE DETENTION IN AERATION TANKS

Factors which influence aeration tank flow-through characteristics are length-to-width ratio, diffuser design, and compartmentation. The Cleveland aeration tank length-to-width ratio (25:1) is comparable to tanks tested in Indianapolis and Baltimore; however, its hydraulic characteristics are less plug flow in nature when compared to the results of dye studies conducted at those plants. The presence of several rows of transverse aerations is unique to the Cleveland tanks. Dye tracer studies conducted at Mansfield, Ohio, have shown that transverse aeration increased longitudinal mixing. Plug-flow characteristics might be more closely approached if the transverse aerators were shut off.

Final Clarifiers - On April 20, one liter of 20 percent Rhodamine WT dye was added to the inlets of Final Clarifiers Nos. 9 and 14 at 11:00 a.m. and 12:00 noon, respectively. These clarifiers are located in different batteries. Samples of both clarifier effluents were collected. The return sludge from Clarifier No. 9 was sampled at the individual sludge well for this clarifier which is located only a short distance from the sludge outlet. Return sludge from Clarifiers Nos. 13 through 16 was sampled at the No. 4 battery return box just prior to mixing with primary effluent. There is little mixing of return sludge between batteries. Total dye accounted for was 65.5 and 71.8 percent for Clarifiers Nos. 9 and 14, respectively. Figures 3 and 4 are graphical plots of dye concentration versus elapsed time after dye addition.

Assuming equal flow distribution, the average mixed liquor inflow to each 900,000-gallon clarifier was 11.3 mgd. The return sludge flow from each clarifier was 2.3 mgd. Therefore, the overflow averaged 9 mgd, and its theoretical displacement time was 2.4 hours. The modal detention time of the final clarifier overflow was 42 percent of the theoretical displacement time, indicating typical circular clarifier performance. The dispersion indices (t_{90}/t_{10}) of the overflow from Clarifiers Nos. 9 and 14 were 4.0 and 3.0, respectively, indicating a greater degree of mixing in Clarifier No. 9. There is no apparent reason for this difference.

The return sludge sampled at Sludge Well No. 9 had a sharp peak in dye concentration occur within 10 minutes after dye addition, indicating limited short circuiting of mixed liquor.

3. Dissolved Oxygen and Sludge Depth

Dissolved oxygen in the aeration tanks was monitored several times during the study period. Typical DO profiles for Aeration Tanks Nos. 9 through 12 were plotted in Figure 5. The unit air flow in these tanks varied from 0.76 to 0.92 cubic foot per gallon of primary effluent.

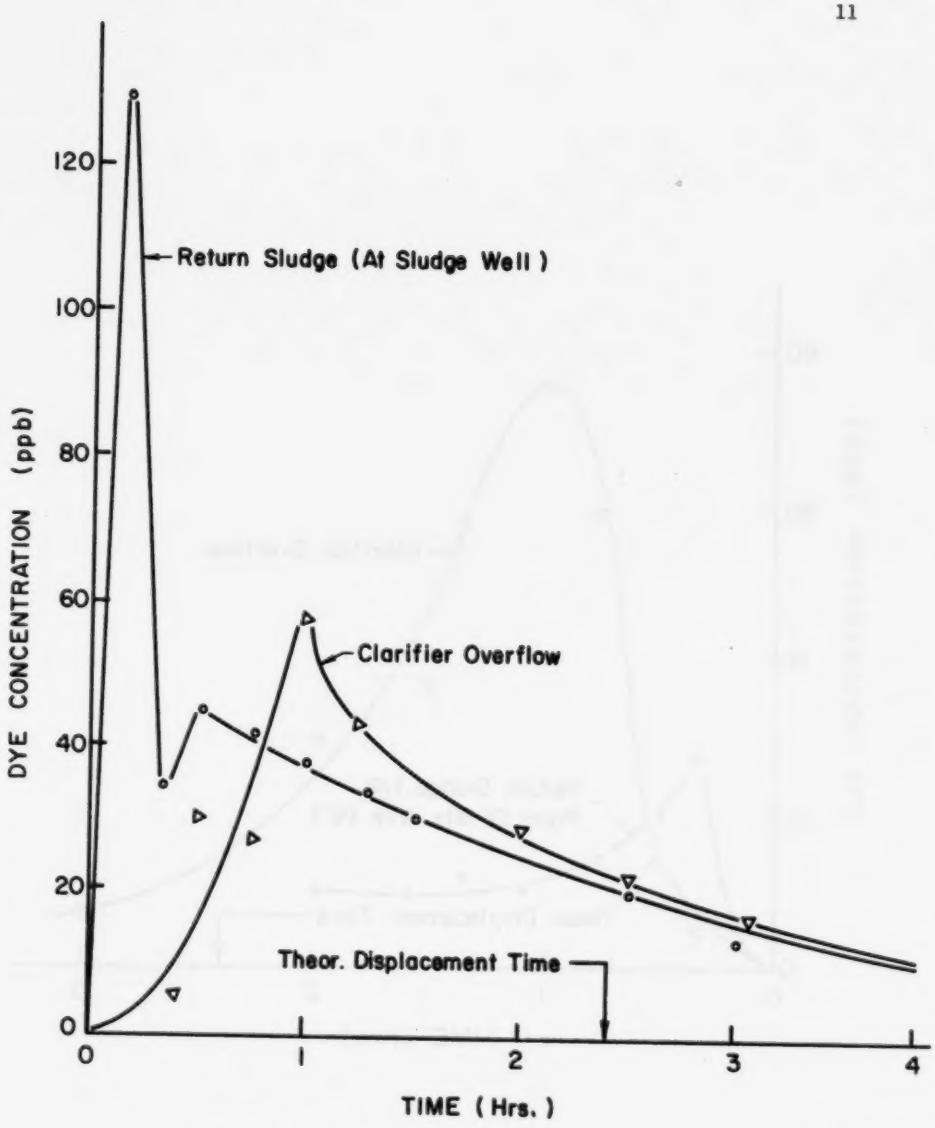

FIGURE 3 – DYE DETENTION – FINAL CLARIFIER NO. 9

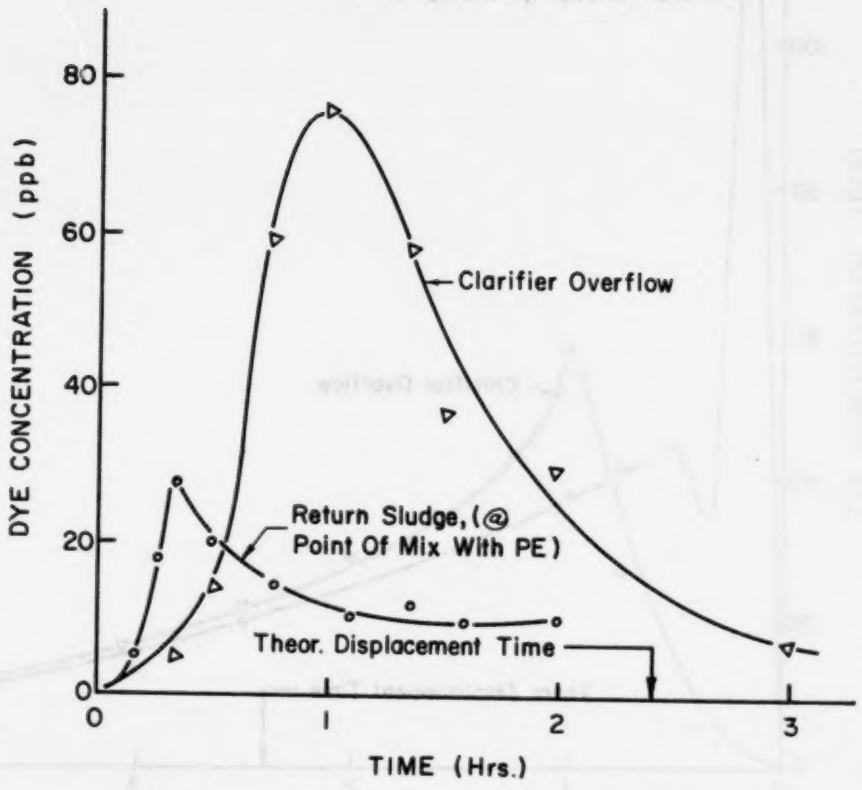

FIGURE 4 – DYE DETENTION - FINAL CLARIFIER NO. 14

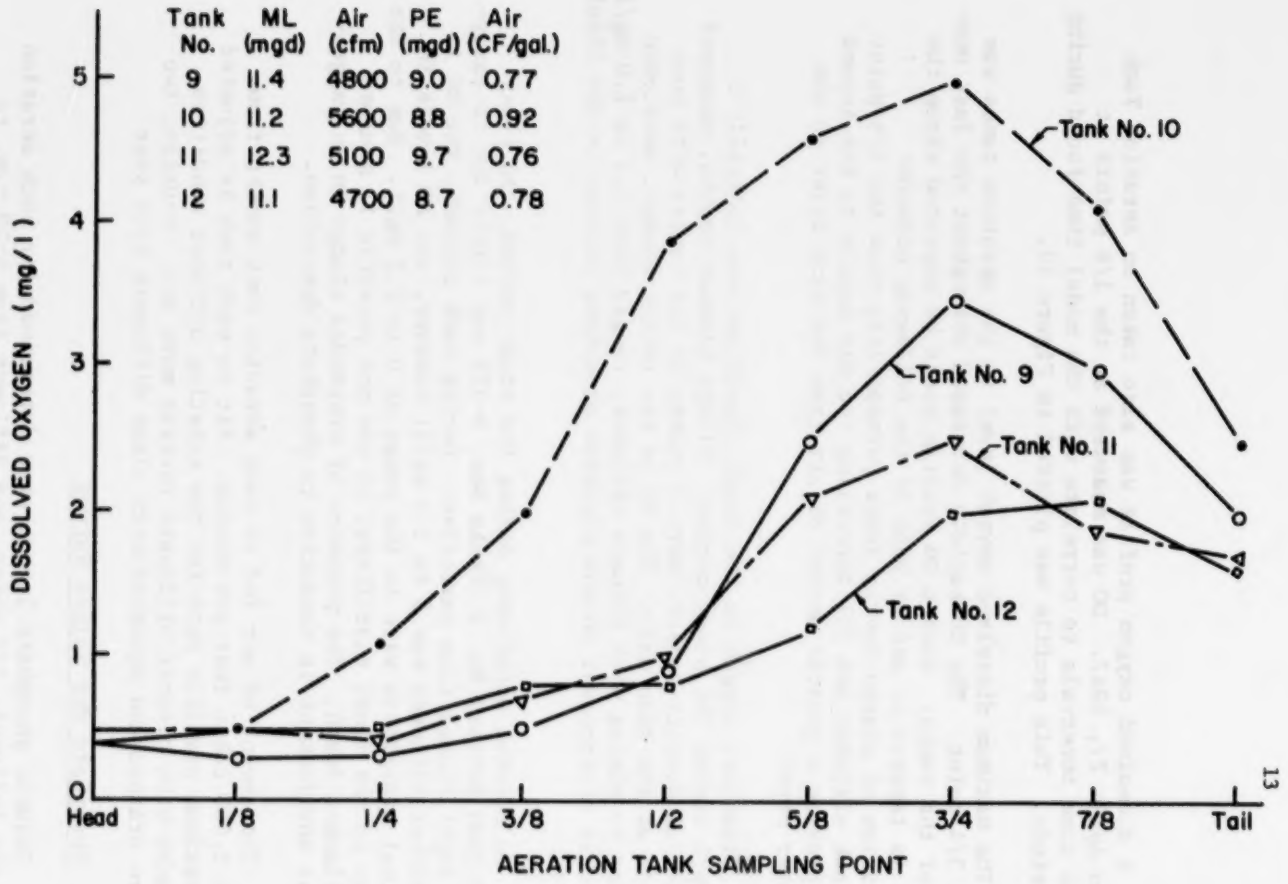

FIGURE 5 — DISSOLVED OXYGEN - AERATION TANKS

A dissolved oxygen profile was also taken on Aeration Tank No. 10 on April 27, 1967. DO was measured at the 1/8 points at staggered time intervals to correlate with the modal time found during the dye study. This profile was plotted in Figure 10.

The maximum dissolved oxygen level in the aeration tanks was near the 3/4 point. The DO rapidly decreased throughout the last one-quarter of the tanks. Such a DO profile would be expected since the aeration is tapered by one or both of the following methods: (1) provision of plates having lower permeability from the 3/4 point to the tank effluent and (2) throttling the air supply to the second pass to provide a greater amount of air from the tank inlet to the one-quarter point.

Dissolved oxygen in the final clarifiers was typically 3 to 3.5 mg/l during the study period. Sludge blanket depths, measured by an optical density sensor, were 3 inches in the center with none detectable at the side wall. The DO in the return sludge, monitored just prior to mixing with primary effluent, ranged from 0.5 to 1.0 mg/l. This aerobic environment should minimize phosphate release in the final clarifiers.

On several occasions, during the study period, the final effluent from Battery No. 3 (Tanks Nos. 9-12) was turbid due to carry-over of light sludge floc particles. During such periods, the DO in the clarifier influent was 3 to 3.5 mg/l; however, the DO levels in these final clarifiers were in the range of 0 to 0.2 mg/l. Due to the turbidity in the final clarifiers, it was not possible to measure sludge blanket depth. The presence of suspended sludge in an oxygen-deficient environment is conducive to phosphate desorption.

The amount of air fed to each aeration tank varied from 4,000 to 5,600 cubic feet per minute. Air to each tank is adjusted to the maximum possible rate for the existing diffuser condition. Thus, tanks with cleaner diffusers receive more air. Usually, two tanks are drained and equipped with clean diffusers each year.

4. Phosphate and Solids Survey

Soluble phosphate levels were determined for each aeration tank at the influent, 1/2 point, and effluent from 4:00 p.m. to 5:00 p.m. on April 18, 1967. The results of this study, given in Table 2, show that soluble phosphate removal averaged 25 percent. In about half of the tanks, the phosphate concentration increased from the 1/2 point to the effluent. The differences in phosphate concentration throughout the aeration tanks could have been due to variation in previous influent concentration.

Table 2

Easterly Water Pollution Control Plant
Cleveland, Ohio

Plant Monitoring Data

Sampling Points	4/18/67 5:00 p.m.					4/20/67 10:30 p.m.	4/20/67 9:00 p.m.	4/20/67 5:30 p.m.		
	in	$O\text{-}PO_4$ as P 1/2	out	% Rem.	TSS	TSS	TSS	in	$O\text{-}PO_4$ as P 1/2	out
AT No. 1	4.7	2.1	2.1	55.3	-	-	-	-	-	-
AT No. 2	2.7	2.3	2.1	21.0	1516	-	-	-	-	-
AT No. 3	2.6	2.4	2.1	21.0	-	-	-	-	-	-
AT No. 4	2.6	2.4	2.0	23.5	-	-	-	-	-	-
AT No. 5	2.5	2.3	1.9	25.2	-	-	-	-	-	-
AT No. 6	2.6	2.2	2.0	23.1	-	-	-	-	-	-
AT No. 7	3.9	2.2	3.0	24.4	1520	-	-	-	-	-
AT No. 8	2.7	2.1	2.2	17.0	-	-	-	-	-	-
AT No. 9	3.5	2.3	2.8	18.0	1348	-	-	2.4	2.0	1.7
AT No. 10	3.6	2.1	2.8	21.2	-	-	-	2.4	2.1	1.8
AT No. 11	3.6	2.4	3.0	18.2	-	-	-	2.4	-	-
AT No. 12	3.3	2.1	2.8	23.8	1420	-	-	2.3	2.0	1.9
AT No. 13	3.4	2.3	2.7	20.6	-	-	-	-	-	-
AT No. 14	3.6	2.2	3.1	12.8	-	-	-	-	-	-
AT No. 15	2.4	1.4	1.6	34.1	-	-	-	-	-	-
AT No. 16	2.3	1.6	1.4	39.2	716	-	-	-	-	-
RS No. 1	2.4	-	-	-	6000	-	5840	-	-	-
RS No. 2	2.0	-	-	-	4550	-	-	-	-	-
RS No. 3	2.0	-	-	-	3800	2425	-	-	-	-
RS No. 4	2.4	-	-	-	5650	4900	-	-	-	-
PE	2.2	-	-	-	-	-	-	-	-	-
Raw	2.3	-	-	-	-	-	-	-	-	-
AT No. 5-8	-	-	-	-	-	-	2252	-	-	-

Raw - Raw Sewage
AT - Aeration Tank Mixed Liquors
RS - Return Sludge
PE - Primary Effluent

The total suspended solids in the aeration tank varied from a low of 716 mg/l in Tank No. 16 to a high of 1,520 mg/l in Tank No. 7. Return sludge solids were in the 3,800 to 6,000 mg/l range. Assuming equal flow splitting, the primary effluent loading to each tank was approximately 8 mgd at this time. The average annual primary effluent BOD concentration was 125 mg/l according to plant records. Assuming this waste concentration prevailed, the BOD loading was about 35 pounds/day/100 pounds MLSS.

5. Extensive Plant Analyses

Plant performance was surveyed on April 25, 1967. Two of the aeration tanks were monitored. Samples were collected at 7:00 a.m. and 12:30 p.m. to determine performance under the conditions of low and high flow, respectively. Samples were analyzed for soluble and total phosphate, total organic carbon (TOC), and TSS. Results are listed in Table 3. The plant was not removing phosphate during this survey.

The MLSS concentration in the aeration tanks tested was approximately 2,500 to 2,700 mg/l. This range is over 1,000 mg/l higher than the concentrations measured on April 18, 1967. Plant operating personnel were increasing solids in these tanks to increase BOD removal.

Aeration Jug Studies

A series of experiments based on results from the San Antonio and earlier amenability studies were devised to test the sewage and sludge of selected plants with regard to orthophosphate removal. Factors shown to affect the rate and magnitude of orthophosphate removal are: suspended solids, BOD, and orthophosphate concentration; metal precipitants; and sludge condition. The results from these experiments serve as a guide to the disposition of plants tested with regard to utilization for process demonstration.

1. MLSS Variation

On April 20 and 21, 1967, two sets of six jugs each were prepared and aerated to determine the effect of suspended solids on phosphate removal. MLSS concentration ranged from 490 to 4,200 mg/l. Jug components are recorded in Table 4 and the results in Table 5.

Normally, the aeration period for such jug studies was six hours. The low solids experiment was terminated at 4.5 hours since significant phosphate removal had ceased at that time. The high solids experiment was terminated at 3.5 hours due to failure of the monitoring equipment.

Table 3

Easterly Pollution Control Center
Cleveland, Ohio

Extensive Plant Performance Data
(mg/l)
April 25, 1967

Sampling Point	Low Flow Condition - 7:00 a.m.				High Flow Condition - 12:30 p.m.			
	$O\text{-}PO_4$ as P	$T\text{-}PO_4$ as P	TOC	TSS	$O\text{-}PO_4$ as P	$T\text{-}PO_4$ as P	TOC	TSS
Raw	9.2	-	66	-	2.2	-	100	-
PE	1.6	-	53	-	2.6	-	84	-
RS No. 3	4.4	391	17.5	-	3.9	465	17.0	-
AT No. 9								
in	2.6	-	17.0	2672	2.5	-	21.0	2480
1/4 pt.	2.8	183	17.5	-	2.0	165	18.0	-
1/2 pt.	3.0	-	13.0	-	1.8	184	17.0	-
out	3.0	-	18.5	-	2.2	184	14.0	-
AT No. 12								
in	2.4	-	14.5	2692	2.5	-	50.5	2480
1/4 pt.	2.5	186	16.0	-	2.1	177	30.5	-
1/2 pt.	2.8	208	25.0	-	1.8	176	36.0	-
out	3.0	192	17.5	-	2.3	168	13.0	-
FE No. 9-12								
Comp.	2.8	-	26.0	-	2.6	-	26.0	-
Thick. Eff.	3.1	-	30.0	-	2.8	-	26.0	-

Table 4

Suspended Solids Variation--Components[1/]

Low Range Solids, April 20, 1967:

Jug No.	PE	RS	RS (Conc)[2/]	FE	ML
	Liters of Component Added				
1	10	1.7	--	3.3	--
2	10	3.3	--	1.7	--
3	10	5.0	--	--	--
4	10	--	3.35	1.7	--
5	10	--	4.25	0.7	--
6	--	--	--	--	15
Analytical Test	Concentration (mg/l)				
$O\text{-}PO_4$ as P	3.8	3.1	--	--	3.8
TSS	--	3,060	6,120	--	1,960
TOC	--	--	--	--	--

High Range Solids, April 21, 1967:

Jug No.	PE	RS (Conc)[3/]	FE
	Liters of Component Added		
1	10	1.5	3.5
2	10	1.8	3.2
3	10	2.1	2.9
4	10	2.4	2.6
5	10	2.8	2.2
6	10	3.0	2.0
Analytical Test	Concentration (mg/l)		
$O\text{-}PO_4$ as P	1.8	--	1.6
TSS	--	20,870	--
TOC	30	--	15.6

1/Aeration rate for all jugs-17.5 l/min.
2/Sludge concentrated by settling and decanting.
3/Sludge concentrated by dissolved air flotation.

Table 5

Suspended Solids Variation--Results
(mg/l)

Low Solids, April 20, 1967:

Aeration Time-Hrs.	Jug No. 1	2	3	4	5	6
	$O\text{-}PO_4\text{-}P$					
0 (4:00 pm)	3.0	3.1	2.7	3.0	2.7	3.0
1	3.2	2.9	2.7	2.5	2.1	3.0
1.5	1.9	2.1	1.9	1.9	1.9	2.3
2.5	2.0	2.2	2.0	1.9	1.9	2.3
4.5	1.9	2.0	1.8	1.8	1.8	2.3
% $O\text{-}PO_4$ Removed	36.7	35.5	33.3	40.0	33.3	23.3

Analytical Test	Concentration					
MLSS	486	500	1,042	977	1,289	1,642
TOC initial	41.0	30.6	25.5	27.0	24.0	25.9

High Solids, April 21, 1967:

Aeration Time-Hrs.	Jug No. 1	2	3	4	5	6
	$O\text{-}PO_4\text{-}P$					
0 (1:30 pm)	1.5	2.4	1.5	2.2	1.6	1.5
3.5	0.8	0.8	0.7	0.8	0.6	0.5
% $O\text{-}PO_4$ Removed	46.7	66.7	53.3	63.6	62.5	66.7

Analytical Test	Concentration					
MLSS	2,196	2,400	2,744	3,216	3,816	4,204
TOC initial	21.0	17.4	19.0	21.3	14.8	20.2

Jug No. 6 of the low solids experiment was composed of mixed liquor from the head of an aeration tank. It served as a control for comparing removal efficiency of plant mixed liquor with jug synthetic mixed liquor. The removal efficiency of this jug was about 10 percent lower than the other jugs.

Figure 6 is a plot of percent orthophosphate removed versus mixed liquor suspended solids concentration. The distribution of results is somewhat scattered, due to the inconsistent initial orthophosphate concentrations. The distribution does show removal to increase with increasing suspended solids concentration. Therefore, a MLSS range of 4,000 to 4,500 mg/l was chosen for subsequent studies. Plant personnel felt that at least one battery of aeration tanks could be operated at this level for an extended period of time.

2. BOD Variation

A set of jugs was prepared on April 24, 1967, to determine the effect of variation in primary effluent BOD concentration on phosphate removal.

Table 6 shows the components of the aeration jugs and the results of analytical tests of such components. The BOD of the primary and final effluents were assumed to be equivalent to the annual averages obtained from plant records, i.e., 125 and 25 mg/l, respectively. Final effluent was added to Jugs Nos. 1 and 2 to dilute the primary effluent concentration to 30 and 60 mg/l, respectively. The BOD in Jug No. 3 was not altered. Jugs Nos. 4, 5, and 6 were supplemented with Metrecal to produce estimated BOD concentration of 190, 250, and 375 mg/l, respectively. The mixture of return sludge and primary effluent was proportioned to produce a MLSS concentration of 4,000 to 4,500 mg/l.

This study was repeated on April 25. The results are shown in Table 7. The first study on April 24 was not considered acceptable due to an error in jug makeup which resulted in jug MLSS concentrations of 7,000 to 8,500 mg/l rather than the desired 4,000 to 4,500 mg/l. Mixed liquor suspended solids concentration in the second set of jugs was in the range 3,500 to 4,500 mg/l.

The data show a 20 percent increase in removal as BOD increased. The increase, however, is of minor significance due to the small reduction in phosphate concentration. Subsequent experiments were run using primary effluent as the nutrient source without benefit of Metrecal supplement.

Soluble total organic carbon concentration of the contents of each jug was determined before and after addition of return sludge for the study with the lower suspended solids content and after solids addition for

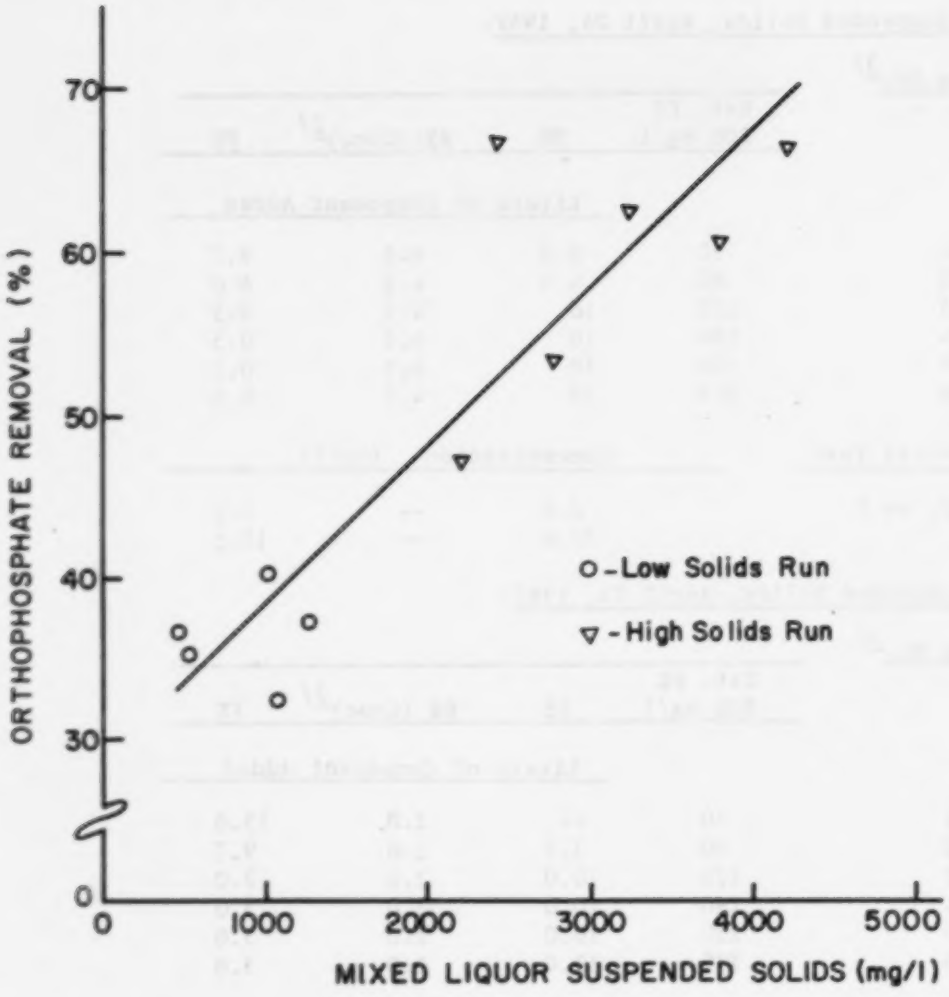

FIGURE 6 – ORTHOPHOSPHATE REMOVAL VS MLSS

Table 6

BOD Variation--Components[1]

High Suspended Solids, April 24, 1967:

Jug No.[3]	Est. PE BOD mg/l	PE	RS (Conc)[2]	FE
		Liters of Component Added		
1	30	0.8	4.5	9.7
2	60	4.5	4.5	6.0
3	125	10	4.5	0.5
4	190	10	4.5	0.5
5	250	10	4.5	0.5
6	375	10	4.5	0.5

Analytical Test	Concentration (mg/l)		
O-PO_4 as P	2.5	--	1.2
TOC	71.0	--	17.5

Low Suspended Solids, April 25, 1967:

Jug No.[3]	Est. PE BOD mg/l	PE	RS (Conc)[2]	FE
		Liters of Component Added		
1	30	--	2.0	13.0
2	60	3.3	2.0	9.7
3	125	10.0	2.0	3.0
4	190	10.0	2.0	3.0
5	250	10.0	2.0	3.0
6	375	10.0	2.0	3.0

Analytical Test	Concentration (mg/l)		
TSS	--	29,320	--
TOC	61-75	--	24

1/Aeration rate for all jugs-17.5 l/min.
2/Concentrated by air flotation (25,700 mg/l).
3/2.6, 5.2, and 10.4 ml of Metrecal added to Jugs No. 4, 5, and 6, respectively. Metrecal contains 1.1 mg/ml O-PO_4 as Phosphorus and 290 mg/ml of BOD.

Table 7

BOD Variation--Results
(mg/l)

High Suspended Solids, April 24, 1967:

Aeration Time-Hrs.	Jug No. 1	2	3	4	5	6
	$O\text{-}PO_4\text{-}P$					
0 (3:00 p.m.)	1.6	2.3	2.6	3.1	3.1	2.9
2	1.5	1.9	2.5	2.4	2.5	2.3
3	1.5	1.7	2.1	2.0	2.0	1.8
4	1.5	1.7	2.1	2.1	2.1	1.9
5	1.6	1.8	2.2	2.1	2.1	1.9
6	1.7	1.9	2.3	2.2	2.2	2.0
% Removed	—	26.1	19.2	35.5	35.5	37.9
ML Settled (45 min.)	1.7	1.9	2.4	2.3	2.3	2.2
Analytical Test	Concentration					
MLSS	8,431	7,518	7,785	7,837	7,770	6,951
TOC-Initial	24.5	34.0	33.5	34.5	44.0	46.0

Low Suspended Solids, April 25, 1967:

Aeration Time-Hrs.	Jug No. 1	2	3	4	5	6
	$O\text{-}PO_4\text{-}P$					
0 (3:00 p.m.)	2.3	2.4	2.3	2.6	2.7	2.7
1	1.9	2.1	2.1	2.0	2.3	2.2
2	1.9	1.9	1.8	1.8	1.9	1.8
3	1.8	1.8	1.7	1.8	1.8	1.7
4	1.8	1.9	1.8	1.8	1.8	1.7
5	1.8	1.8	1.8	1.8	1.7	1.6
6	2.1	2.0	2.0	2.0	1.8	1.6
% Removed @ 5 hrs.	21.7	25.0	21.7	30.8	37.0	40.7
ML Settled (30 min.)	2.1	2.0	1.9	1.9	1.8	1.6
Item	TSS					
Mixed Liquor	3,724	3,554	3,572	3,540	3,944	3,672
	TOC					
PE + Metrecal	12.0	33.5	72.0	87.0	107.0	94.0
Filtered ML	24.5	22.5	31.0	35.5	50.5	54.0
Settled Supernatant	22.0	23.0	17.5	50.5	53.5	51.0

the study with the higher suspended solids content. These "before and after" data plotted in Figure 7 show an increase in carbon with an increase in estimated BOD and considerable adsorption of carbonaceous material by activated sludge solids within 5 minutes after addition of the solids.

3. Soluble Orthophosphate Variation

Five jugs were prepared on April 26, 1967, to determine the effect of soluble orthophosphate concentration on its removal and rate of removal. The BOD of the primary effluent was not altered. Jug components are given in Table 8.

Since orthophosphate concentration of the primary effluent was consistently low, it was used as the base line for this study. Jug No. 1 was set up at normal phosphate concentration as a control. Potassium dihydrogenphosphate was added to Jugs Nos. 2, 3, and 4, respectively, to produce initial orthophosphate concentrations of 200, 250, and 300 percent of the control. MLSS concentration ranged from about 3,400 to 4,000 mg/l. An additional jug (Jug No. 5) was run with the phosphate variation jugs containing mixed liquor from the influent end of an aeration tank. The orthophosphate content was increased 2.5 times that of the aeration tank mixed liquor to determine its reaction to increased phosphate load and for comparison with the synthetic mixed liquor Jug No. 3. The results are recorded in Table 8. The data show percent removal decrease as initial $O\text{-}PO_4$ concentration increases with the same BOD and MLSS concentrations.

The rate and magnitude of phosphate removal, however, does not seem to be altered by increased initial $O\text{-}PO_4$ concentration as shown by the similarity in removal of Figure 8.

Comparison of Jugs Nos. 3 and 5 show that Jug No. 3 removed 50 percent more phosphate than Jug No. 5. The MLSS in Jug No. 3, however, was also 50 percent higher than Jug No. 5.

4. Chemical Addition

Three jugs were set up April 27, 1967, to determine the effect of iron and aluminum salts on soluble orthophosphate removal. The mixed liquor was prepared using primary effluent and return sludge. Orthophosphate concentration was determined after thorough mixing. Jug No. 1 served as a control. Jugs Nos. 2 and 3 were dosed with 25 mg/l of ferric and aluminum ion, respectively. Aluminum sulfate and ferric chloride were the chemicals used. After chemical addition and thorough mixing, soluble orthophosphate concentration was immediately determined. MLSS concentration ranged from 4,000 to 4,300 mg/l.

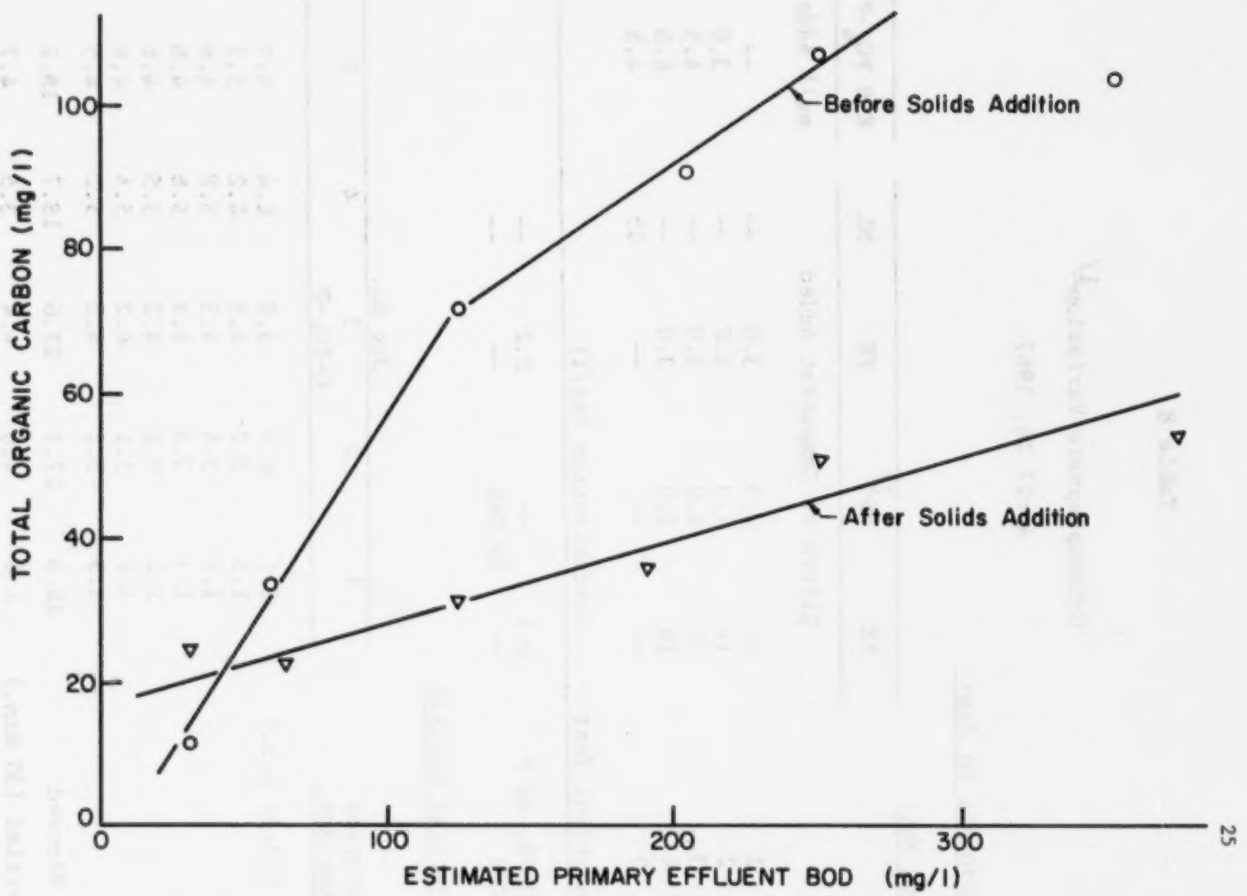

FIGURE 7- TOC - BOD RELATIONSHIPS

Table 8

Orthohposphate Variation[1/]

April 26, 1967

Components in Jugs

Jug No.	PE	RS[2/]	FE	ML	$K_2H\ PO_4$-P
	Liters of Component Added				mg/l Added
1	10	2.0	3.0	--	--
2	10	2.0	3.0	--	3.0
3	10	2.0	3.0	--	4.5
4	10	2.0	3.0	--	6.0
5	--	--	--	15	4.5
Analytical Test	Concentration (mg/l)				
$O\text{-}PO_4$ as P	2.1	--	2.2	--	
TSS	--	29,060	--	--	

Analytical Results

Aeration Time-Hrs.	Jug No. 1	2	3	4	5
	$O\text{-}PO_4$-P				
0 (12:30 p.m.)	2.1	4.4	5.8	6.4	5.5
1	1.5	3.7	4.8	6.2	5.2
2	1.4	3.5	4.5	5.8	4.9
3	1.3	3.3	4.3	5.6	4.8
4	1.1	3.2	4.2	5.5	4.6
5	1.3	3.1	4.2	5.4	4.6
6	1.3	3.2	4.2	5.2	4.5
% Removed	38.0	27.3	27.6	18.7	18.2
Settled (30 min.)	1.4	4.6	4.4	3.5	4.7
Analytical Test	Concentration (mg/l)				
TSS	3,978	3,696	3,389	3,702	2,264

1/Aeration rate for all jugs - 17.5 l/min.
2/Concentrated by dissolved air flotation.

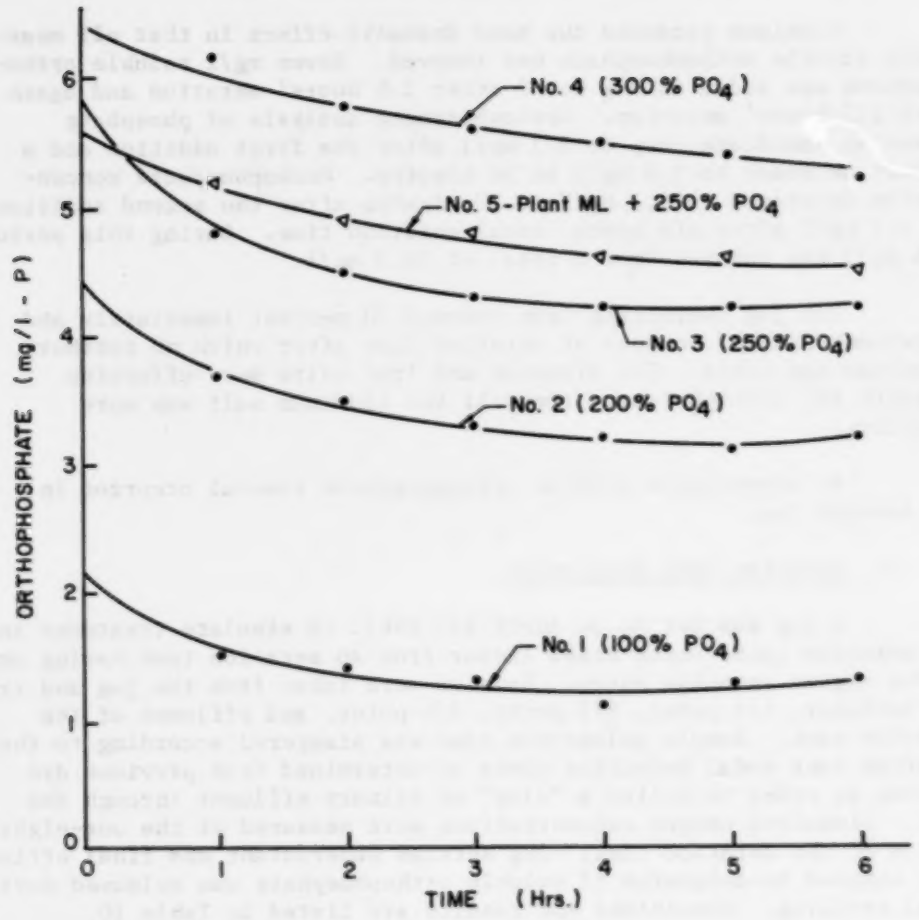

FIGURE 8 - PHOSPHATE VARIATION – AERATION JUGS

The jug components and results are recorded in Table 9 and the results shown graphically in Figure 9. Addition of iron and aluminum resulted in immediate orthophosphate removal.

Aluminum produced the most dramatic effect in that all measurable soluble orthophosphate was removed. Seven mg/l soluble orthophosphate was added to Jug No. 2 after 1.5 hours' aeration and again after 2.5 hours' aeration. Orthophosphate analysis of phosphate showed an immediate drop to 3.7 mg/l after the first addition and a further decrease to 1.8 mg/l in 30 minutes. Orthophosphate concentration decreased to 6.1 mg/l in 30 minutes after the second addition and 4.7 mg/l after six hours' total aeration time. During this period, 11.6 mg/l was removed from a total of 16.3 mg/l.

The jug containing iron removed 70 percent immediately and 87 percent within one hour of aeration time after which no further reduction was noted. The aluminum and iron salts were effective reagents for orthophosphate removal; the aluminum salt was more effective.

No appreciable soluble orthophosphate removal occurred in the control jug.

5. Aeration Tank Simulation

A jug was set up on April 27, 1967, to simulate treatment in the aeration tanks using mixed liquor from an aeration tank having one of the higher aeration rates. Samples were taken from the jug and from the influent, 1/4 point, 1/2 point, 3/4 point, and effluent of the aeration tank. Sample collection time was staggered according to the aeration tank modal detention times as determined from previous dye studies in order to follow a "slug" of primary effluent through the tank. Dissolved oxygen concentrations were measured at the one-eighth points of the aeration tank. Jug settled supernatant and final effluent were sampled to determine if soluble orthophosphate was released during final settling. Conditions and results are listed in Table 10.

Figure 10 is a plot of orthophosphate and dissolved oxygen concentration versus aeration time. Both the aeration tank and jug removed about 30 percent of the orthophosphate. The jug closely simulated the aeration tank during this study.

6. Sludge Acclimation

A jug was set up at 6:30 p.m. on April 25, 1967, to acclimate the return sludge to a high level of orthophosphate removal. Jug components consisted of 10 liters of return sludge and 5 liters of primary effluent. A Metrecal solution was continuously fed to simulate

Table 9

Chemical Addition[1/]

April 27, 1967

Components in Jugs

Jug No.	PE	RS[2/]	FE	Fe^{+3}	Al^{+3}
	Liters of Component Added			mg/l Added	
1	10	2.4	2.6	--	--
2	10	2.4	2.6	--	25
3	10	2.4	2.6	25	--

Analytical Test	Concentration (mg/l)		
$O\text{-}PO_4$ as P	2.6	--	1.9
TSS	--	26,260	--

Analytical Results

Aeration Time-Hrs.	Jug No. 1	2	3
	$O\text{-}PO_4$ (mg/l-P)		
-0.1 (12:00 N)[4/]	2.1	2.3	2.3
0 [5/]	--	0.0	0.7
1	1.8	0.1	0.3
1.5	--	3.7[3/]	--
2	1.8	1.8[3/]	0.3
3	1.8	6.1	0.3
4	1.9	5.6	0.3
5	2.0	4.9	0.3
6	2.0	4.7	0.3

Analytical Test	Concentration (mg/l)		
TSS	4,304	3,976	4,096

1/Aeration rate for all jugs-17.5 l/min.
2/Concentrated by air flotation.
3/Seven mg/l $O\text{-}PO_4$ as P added before sampling.
4/Before chemical addition.
5/After chemical addition.

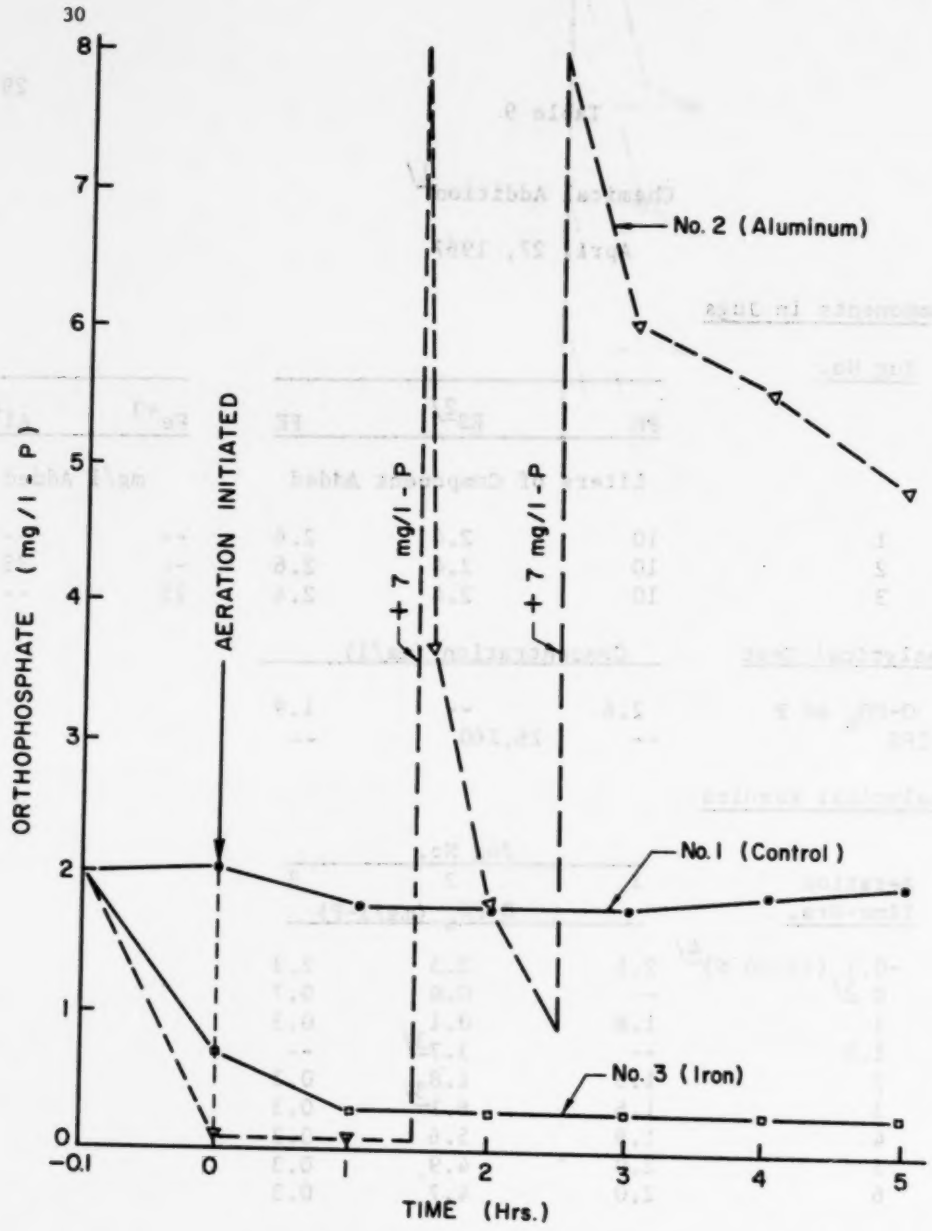

FIGURE 9- CHEMICAL ADDITION - AERATION JUGS

Table 10

Aeration Tank-Jug Simulation

April 27, 1967

Sampling Point	Time of Sampling	$O\text{-}PO_4$ (mg/l-P)	
		Jug[1/]	Aeration Tank[2/]
AT, Head, & Jug ML	1:30 p.m.	2.6	2.7
AT, 1/4 pt., & Jug ML	2:15 p.m.	2.1	2.3
AT, 1/2 pt., & Jug ML	3:00 p.m.	1.9	2.1
AT, 3/4 pt., & Jug ML	4:15 p.m.	1.8	2.1
AT, Tail, & Jug ML	5:00 p.m.	1.8	1.9
Jug Effl. (10-min. settling)	5:10 p.m.	1.8	--
Jug Effl. (60-min settling)	6:00 p.m.	2.0	--
FE (Clarifiers No. 9-12)	5:45 p.m.	--	2.0
FE (Clarifiers No. 9-12)	6:00 p.m.	--	1.9
FE (Clarifiers No. 9-12)	6:15 p.m.	--	1.9

1/Jug makeup was 15 liters of mixed liquor taken from the head of Aeration Tank No. 10. MLSS Concentration = 2,368 mg/l. Jug aeration rate-17.5 liters/min.

2/MLSS concentration = 2,296 mg/l.

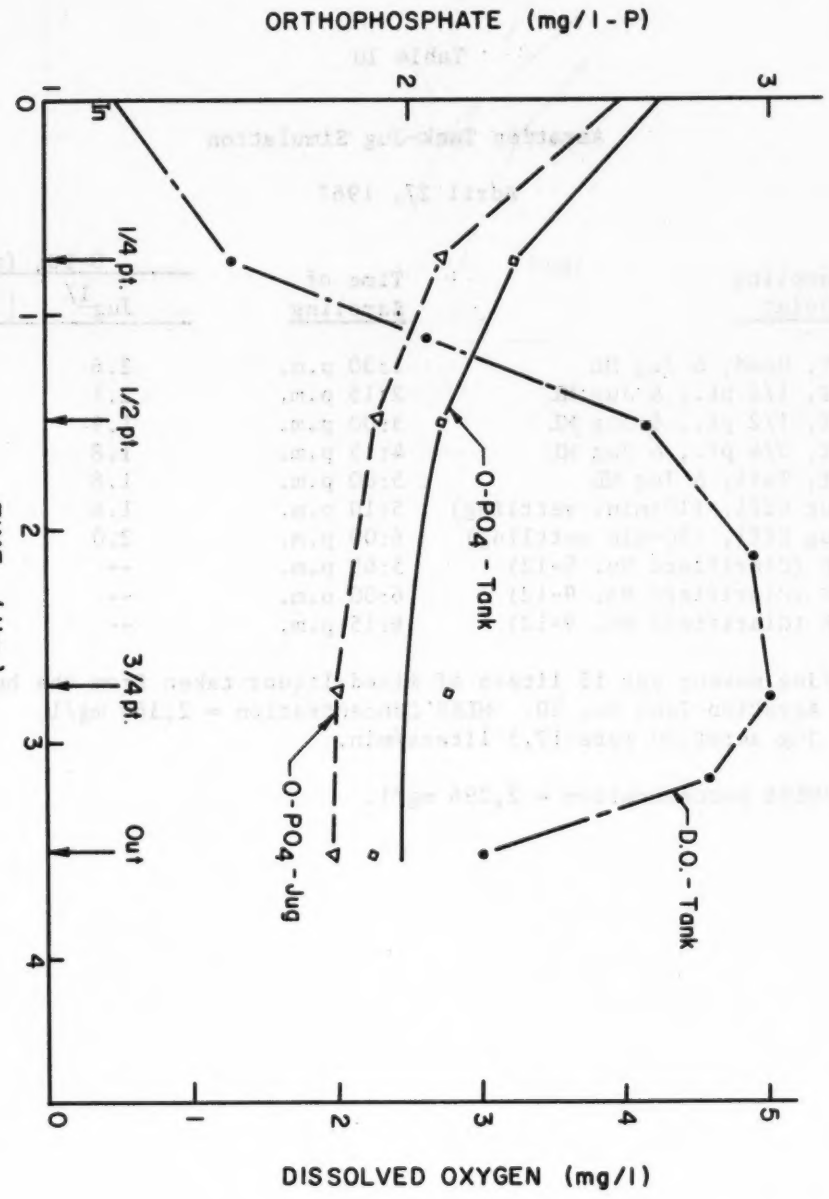

FIGURE 10- AERATION TANK & JUG COMPARISON

a unit BOD loading varying from 0.2 to 0.8 lb/day/lb of MLSS. Metrecal contains 290 mg/ml of BOD and 1.1 mg/ml of $O\text{-}PO_4$ as P. Additional soluble orthophosphate was periodically added to the system to maintain a favorable environment.

The acclimated jug was dosed with phosphate and Metrecal and aerated overnight at a rate of 17.5 liters/minute on three successive occasions. The total amount of soluble orthophosphate added ranged from 13 to 18 mg/l. Phosphate removal varied from 53 to 67 percent.

Between periods of overnight feeding, the acclimation jug was monitored concurrently with the orthophosphate variation and chemical addition experiments. At the beginning of these experiments, the acclimation jug was decanted and replenished with primary effluent as described. Neither Metrecal nor supplemental phosphate was added during these monitoring periods. Thus, the acclimated sludge was exposed to the same environment as the "control" jugs of these experiments.

The analytical results are shown in Table 11. On April 26, the phosphate removal was 55 percent in the acclimation jug and 38 percent in the control. The MLSS concentration of the acclimation jug was 30 percent higher than the control. On April 27, the acclimation jug removed 44 percent, whereas, the control jug removed 5 percent. The MLSS concentration of the acclimation jug was 13 percent higher than the control on this date.

These data show increased removal as a result of the acclimation procedures applied.

Sewage Characterization

Characterization of samples from the various unit processes of activated sludge plants and an aeration jug with regard to selected chemical parameters were included in the investigation. Samples were taken from a jug study whose conditions and constituents were those which resulted in maximum phosphate removal. The investigations were undertaken to determine trends or correlations between parameters which would be useful in defining the phosphate removal process. Frequently, phosphate removal from jug aeration was higher than that in the aeration tanks. During such instances, the probability of identifying significant differences was greatly enhanced by characterizing the components in the jug.

The samples were analyzed with and without suspended solids to differentiate between the quantity of each respective chemical parameter associated with the solids and that associated with the

Table 11

Acclimation-Control Comparison[1/]
April 26-28, 1967
$O\text{-}PO_4$ as P (mg/l)

Aeration Time (Hours)	4/26/67 Acclimation Jug	4/26/67 Control Jug[2/]	4/27/67 Acclimated Jug	4/27/67 Control Jug[3/]	4/28/67 Acclimated Jug
0	3.6	2.1	3.9	2.1	4.1
1	--	1.5	2.8	1.8	3.0
2	--	1.4	2.6	1.8	2.7
3	2.2	1.3	2.4	1.8	3.1
4	1.9	1.1	1.9	1.9	--
5	1.7	1.3	2.2	2.0	--
6	1.6	1.3	2.2	2.0	--
% Removal	55.5	38.0	43.6	4.8	24.4
MLSS (mg/l)	5,162	3.978	4.872	4,304	--

1/ Aeration Rate = 17.5 l/min.
2/ Jug Components Listed as Jug No. 1, Table No. 8.
3/ Jug Components Listed as Jug No. 1, Table No. 9.

liquid. Separation was accomplished by first decanting, then centrifuging the resulting supernatant for further solids removal. Samples resulting from such treatment are referred to as centrates of the original sample.

The samples characterized and the results will not be considered in this report since the basic purpose was for comparison with similar data from other plant studies. The data and comparisons thereof are reported under separate cover.[3]

Microbiological Studies

The microbiological studies conducted at the plants tested for amenability to phosphate removal were divided into two phases. Phase I consisted of determining bacterial number by the total plate count method upon analysis of various plant and aeration jug samples. A correlation was sought relating phosphate removal with bacterial population. Phase II consisted of selection of predominant colonial types, transfer to agar slants, and transport to the Ada laboratory for identification. The final portion of this phase is under way. The results for the Cleveland and all other amenability studies are reported under separate cover.[4]

The data from the plate count determinations are recorded in Appendix IV. There is no apparent relationship between suspended solids concentration and bacterial population. The bacterial counts remain essentially constant through the aeration tanks and during the course of the jug runs. Addition of ferric iron and aluminum salts tended to reduce the count but not significantly. No apparent change in count was noted during the course of the acclimation studies.

After comparison of these data, it was concluded that bacterial counts and phosphate removal, if related, was not detectable by the methods employed.

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[3]Lively, L. D. et al., "Phosphate Removal by Activated Sludge, Waste Characterizations," USDI, FWPCA, Robert S. Kerr Water Research Center, Ada, Oklahoma. 1968.

[4]Moyer, J. E. et al., "Survey of Activated Sludge Treatment Plants for Predominant Bacterial Types," USDI, FWPCA, Robert S. Kerr Water Research Center, Ada, Oklahoma. 1968.

SUMMARY

Studies conducted at the activated sludge plant (Easterly Pollution Control Center) in Cleveland, Ohio, April 18-27, 1967, indicated 25 percent orthophosphate removal.

The aeration tanks are two-pass with a length-width ratio of 25:1. Dye tracer studies show that the tank effluent has a dispersion index (t_{90}/t_{10}) of 3.0 and a modal detention time equal to 82 percent of the displacement time. Ten percent of the mixed liquor receives less than 2 hours of aeration and 30 percent less than 3 hours.

Dye tracer studies of the circular final clarifiers indicated that the overflow has a modal detention time equal to one-half the displacement time, and that 25 percent of the return sludge consisted of short-circuited mixed liquor.

The plant mixed liquor suspended solids concentration varied from 1,500 mg/1 to 2,500 mg/1. The return sludge averaged 27 to 30 percent of the primary effluent flow. About 400,000 gal/day of concentrated activated sludge was wasted.

The amount of air supplied ranged from 0.75 to 1.0 cubic feet per gallon of waste treated which resulted in a dissolved oxygen concentration of 2 to 5 mg/1 at the 3/4 point in the aeration tank. Due to reduced air supply throughout the last one-quarter of the tank, the aeration tank effluent contained 1.5 to 2.5 mg/1 of dissolved oxygen. The dissolved oxygen in the final clarifiers was normally 3 to 3.5 mg/1. On several occasions, the effluent from the clarifiers was turbid. During such periods, the dissolved oxygen concentrations in the final clarifiers ranged from 0 to 0.2 mg/1.

Plant records show that phosphate (mg/1-P) in waste streams during April 1966, was as follows:

Source	Ortho		Total		Avg. Ortho/Total
	Min	Max	Min	Max	
Raw Waste	1.2	3.5	5.0	9.5	0.29
Primary Effluent	1.2	4.0	3.3	8.7	0.34
Final Effluent	1.0	3.6	0.9	6.8	0.50

Pilot studies were conducted in aerated jugs to determine the effect on orthophosphate removal resulting from (1) variation in MLSS, BOD, and O-PO_4 concentration; (2) addition of ferric iron and trivalent aluminum; and (3) sludge acclimation.

Removal increased from 36 to 67 percent as the MLSS concentration was increased from 500 to 4,200 mg/l. The MLSS concentrations ranged from 3,500 to 4,000 mg/l in the remaining studies. Variation in primary effluent BOD concentration resulted in removals varying from 22 percent at 30 mg/l to 41 percent at 375 mg/l. These limited removals usually occurred in less than three hours of aeration. Increasing orthophosphate from 100 to 300 percent of the primary effluent concentration decreased removal from 38 to 19 percent.

Addition of 25 mg/l of metal ion resulted in removals of 88 percent with iron salts and near 100 percent with aluminum salts. After acclimating the return sludge for a period of 18 to 42 hours, orthophosphate removal ranged from 44 to 55 percent in the test jug, whereas controls removed 5 to 38 percent.

CONCLUSIONS

Plant Studies

1. During these investigations, the activated sludge facilities at the Easterly Pollution Control Center were not removing a significant quantity of soluble orthophosphate.

2. In the primary effluent, the BOD concentration was about 60 percent, and the soluble phosphate concentration was less than one-half that prevalent in the San Antonio wastes.

3. The aeration tanks exhibit a degree of longitudinal mixing and plug flow comparable to the San Antonio Rilling Plant aeration tanks. Short circuiting of liquid through the aeration tanks is limited, and sufficient aeration time is provided for significant soluble phosphate removal.

4. The Cleveland aeration tanks exhibit a greater degree of longitudinal mixing and less plug-flow characteristics than other aeration tanks having comparable length-to-width ratios. Based on previous studies in Mansfield, Ohio, the transverse aeration in the Cleveland tanks may be the cause of the increased mixing.

5. Conditions normally found in the final clarifiers indicated rapid solids-liquid separation. Dissolved oxygen levels were judged adequate to minimize phosphate release. The flow-through characteristics are indicative of satisfactory clarification performance.

6. Occasionally, conditions found in the final clarifiers indicated inadequate solids-liquid separation. During such occurrences, the low dissolved oxygen levels would be favorable for phosphate release.

7. The flow-through characteristics of the return sludge system indicate that a significant amount of mixed liquor short-circuits directly to the return sludge outlet. This phenomenon is indicative of little sludge accumulation in the final clarifier and is similar to that observed in the San Antonio Rilling Plant.

Jug Studies

1. Orthophosphate removal increased with increasing MLSS concentration.

2. At constant MLSS concentration, orthophosphate removal increased slightly with additional BOD.

3. At constant suspended solids and BOD concentrations, orthophosphate removal decreased slightly with increased initial orthophosphate concentration.

4. Ferric iron and aluminum ion are effective agents for orthophosphate removal. Aluminum was more effective than iron.

5. Bacterial plate count does not correlate with orthophosphate removal.

6. Return sludge subjected to a period of acclimation removed significantly greater quantities of orthophosphate.

7. Based on the results of aeration jug studies, it is concluded that the amenability of the sludge to phosphate removal is "probable" when compared with the following scale:

Questionable	-	0 to 25% removal
Probable	-	25 to 75% removal
Conclusive	-	75 to 100% removal

RECOMMENDATIONS

1. The Easterly Pollution Control Center at Cleveland, Ohio, is not recommended for demonstration of biological phosphate removal by activated sludge unless subsequent investigations indicate that the waste and sludge are definitely amenable.

2. The following additional investigations and periods of trial operation should be undertaken to more adequately determine the waste's amenability to orthophosphate removal:

a. Determine the effect of cutting off the air supply to the transverse aeration plates in one of the aeration tanks.

b. Test the primary effluent to more adequately determine the diurnal variation in ortho and total phosphate concentrations.

c. Optimize operating parameters considered essential for phosphate removal and operate a four-tank battery under such conditions until it adapts to the modified environment. The results of amenability studies indicate that the following operational changes should be tried:

(1) Increase MLSS concentration to a maximum practical level (4,000 mg/l).

(2) Equalize aeration rate through aeration tanks.

(3) Reduce the primary effluent inflow when additional aeration time is required.

(4) Increase the BOD concentration of the primary effluent by removing a portion of the primary clarifiers from service and increase aeration rate.

3. If a significant amount of phosphate removal is experienced during the periods of trial operation, the Easterly Pollution Control Center, because of its flexibility in design and operation, would be most desirable as a demonstration site.

APPENDIXES

Appendix I

Analytical Procedures

by

B. L. DePrater

Sample Preparation

Samples collected for analyses in the field were processed as outlined in the following analytical procedures.

Samples returned to the Robert S. Kerr Water Research Center are referred to as whole, centrate, whole fixed, and centrate fixed.

The following table lists the treatment each type received prior to shipment to Ada.

Sample	Treatment
1. Whole	None
2. Whole Fixed	One (1) ml conc. sulfuric acid per liter of sample.
3. Centrate	The sample was passed through a Sharples motor driven laboratory model continuous centrifuge, equipped with a clarifier bowl driven at 23,000 rpm. The sample was delivered to the centrifuge by a peristaltic pump at a feed rate of 150 ml/min. The bowl was cleaned and rinsed with distilled water after each sample.
4. Centrate Fixed	The centrate sample plus 1 ml/l conc. sulfuric acid.

All samples were shipped in either 250 or 1,000 ml polyethylene containers.

Chemical Tests

1. Orthophosphate

In the field, initial samples for orthophosphate were filtered immediately using Schleicher and Schuell No. 588 paper. Subsequent analysis by the stannous chloride procedure in Standard Methods[1] included the use of a B&L Spectronic 20 at 690 mμ.

A continuous automatic sampling device, built specifically to support jug-study phosphate analyses, supplied whole samples to a Technicon AutoAnalyzer platformed according to the method by Gales and Julian.[2] The manifold and reagents were modified, however, to more closely approximate Standard Methods.[1] The arrangement, in order of sequence, was as follows:

a. A six-port peristaltic pump circulating jug mixed liquor continuously.

b. An open-shut solenoid valve system selectively sampling the flow from a T-connection in each circulating jug line.

c. A stepping relay alternately activating one of six jug sample solenoids or the solenoid to a distilled wash water supply.

d. A master timer regulating the stepping relay at two-minute intervals.

e. A Technicon proportioning pump providing the flow of samples and distilled water to a Technicon continuous filter. This pump also diluted filtered samples with distilled water in the ratio of 1:40, respectively.

Whole plant samples were run on the Technicon AutoAnalyzer using a Technicon Sampler II and a continuous filter with samples reaching the filter within 30 minutes. No significant orthophosphate bleedback occurred in unfiltered samples during this period.

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[1]Standard Methods for the Examination of Water and Wastewater, 12th Edition (Method B), p. 234-236. 1965.

[2]M. E. Gales, Jr., and E. C. Julian, "Determination of Inorganic Phosphate or Total Phosphate in Water by Automatic Analysis." Presented at the 1966 Technicon Symposium on Automation in Analytical Chemistry.

2. Total Phosphate

Analyses were conducted on fixed whole samples at the Ada laboratory within 15 days of sample collection. Initially whole samples were blended for three to five minutes in a Waring blendor and then analyzed by the persulfate procedure of Gales and Julian.[2] The procedure was modified to more closely approximate the Standard Methods[1] procedure for orthophosphate in that the samples were neutralized after digestion. Also the manifold design and reagents for the AutoAnalyzer were adjusted to deliver approximately the amount of reagents per sample outlined by Standard Methods.[1]

3. Total Carbon and Total Nonvolatile Organic Carbon[1]

Whole samples were run in the field using the methods of Van Hall, Safranko, and Stenger[3] and Van Hall, Barth, and Stenger.[4] A Beckman Carbonaceous Analyzer was used. Preliminary homogenization in a Waring blendor provided representative syringe sampling of whole samples. As the whole acidified sample was further purged with nitrogen gas for five minutes, results were reported as total nonvolatile organic carbon. Acetic acid standards were used for instrument calibration.

Physical Tests

1. Solids

Tests for total suspended and total volatile suspended solids were conducted according to Standard Methods.[5] Reeve Angel 2.4-cm glass fiber filters grade 934AH were used in lieu of asbestos mats. Gooch crucibles were fired at 600°C, cooled, the mats placed in the crucibles and dried at 103°C for at least 1 hour before initial weighing. At intervals, crucibles with filters were subjected to 600°C furnace temperatures to check for weight loss due to the filter. Total and total volatile solids were determined according to Standard Methods.[6]

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[3]Analytical Chemistry, 35:3, p. 315-319. 1963.

[4]C. E. Van Hall, D. Barth, and V. A. Stenger, "Elimination of Carbonates from Aqueous Solutions Prior to Organic Carbon Determination," Anal. Chem. 37:6, 769. 1965.

[5]Standard Methods for the Examination of Water and Wastewater, 12th Edition (Methods C & D), p. 424-425. 1965.

[6]Standard Methods for the Examination of Water and Wastewater, 12th Edition (Methods A & B), p. 423-424. 1965.

2. Dissolved Oxygen

Measurements were made in situ with a YSI Model 51 Oxygen Meter equipped with a Model 5103 oxygen/temperature probe. The meter was calibrated against the Azide Modification of the Winkler Method described in Standard Methods.[7] The meter was also calibrated against saturated air at the temperature of the test medium.

3. Hydrogen Ion Concentration

All pH measurements were made using a line current Beckman Zeromatic II equipped with glass and calomel electrodes. Measurements were made on whole-untreated samples.

4. Temperature

Temperature measurements were made with a battery powered thermistor-thermometer.

NOTE: Mention of products and manufacturer is for identification only and does not imply endorsement by the Federal Water Pollution Control Administration or the U. S. Department of the Interior.

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[7]Standard Methods for the Examination of Water and Wastewater, 12th Edition (Method A), p. 406-410. 1965.

Appendix II

Easterly Pollution Control Center
Cleveland, Ohio

PHOSPHATE MONITORING

Date	Total Phosphate PO_4 - ppm Raw	Sett	Eff	Dissolved Phosphate PO_4 - ppm Raw	Sett	Eff
4/3/66	19.2	19.2	10.4			
4/4/66	22.0	24.8	16.0	4.0	5.4	5.4
4/5/66	25.2	18.4	16.8	10.6	7.4	9.0
4/6/66	18.4	19.6	10.4	8.0	8.2	7.8
4/7/66	18.4	19.6	16.0	7.0	7.2	7.2
4/10/66	20.8	22.0	11.2	5.4	6.6	7.4
4/11/66	22.0	19.2	14.0	9.2	9.8	8.8
4/12/66	28.4	26.0	20.4	4.4	5.2	5.2
4/13/66	24.0	21.0	13.2	9.2	9.2	6.8
4/14/66				7.8	7.8	7.4
4/17/66	23.2	21.6	17.6	10.2	9.8	8.2
4/18/66	25.0	18.7	17.3	8.8	10.8	10.8
4/19/66	15.0	16.1	14.0	8.7	8.7	9.4
4/20/66	18.7	17.3	12.0	13.7	12.0	10.1
4/21/66	19.0	14.7	2.7			
4/24/66	15.0	12.7	9.0	3.8	5.2	4.9
4/25/66	16.3	17.4	10.7	3.5	4.7	5.0
4/26/66				4.3	5.9	6.4
4/27/66	15.0	10.0	8.0	3.8	3.7	4.7
4/28/66		13.4	6.7		4.7	3.2
Max.	28.4	26.0	20.4	13.7	12.0	10.8
Min.	15.0	10.0	2.7	3.5	3.7	3.2
Avg.	20.3	18.4	12.6	7.0	7.4	7.3
% Reduction		9.4	37.9			
5/1/66	16.0	14.4	12.4	9.0	8.7	8.5
5/2/66				5.8		6.7
5/3/66				4.2		6.8
5/4/66	13.4	12.0	8.0	3.8	3.3	4.3
5/5/66	15.7	13.5	9.4	5.4	3.0	4.3
5/8/66	13.4	11.7	11.4	7.5	8.2	8.0
5/9/66	9.1	9.1	8.1	6.7	5.8	4.9
5/10/66	9.1	8.0	8.7	5.2	5.0	6.0
5/11/66	14.8	11.4	11.4	3.7	3.3	4.3

Appendix II (Cont'd.)

Date	Total Phosphate PO_4 - ppm Raw	Sett	Eff	Dissolved Phosphate PO_4 - ppm Raw	Sett	Eff
5/12/66	15.0	13.7	10.7	3.4	3.0	2.7
5/15/66					3.0	1.5
5/16/66	16.4	15.4	15.4	11.1	9.4	10.1
5/17/66		19.7	19.4		7.9	10.1
5/18/66		13.3	11.7		7.0	4.7
5/19/66	16.9	15.5	9.7	8.2	7.2	5.9
5/22/66	18.4	19.4	11.7	14.4	12.4	9.4
5/23/66	25.4	16.7	13.3	8.3	8.3	9.2
5/24/66	21.4	18.7	16.7	16.1	13.7	12.0
5/25/66	25.0	25.4	17.7	10.2	8.7	7.7
5/26/66	25.4	24.7	10.4	7.0	8.7	0.7
5/30/66		13.7	12.4		12.3	12.0
5/31/66	16.4	13.5	10.1	9.0	8.0	8.4
Max.	25.4	25.4	19.4	16.1	13.7	12.0
Min.	9.1	8.0	8.0	3.4	3.0	0.7
Avg.	17.2	15.2	12.1	7.9	7.3	6.7
% Reduction		11.6	29.7		7.6	15.2
6/1/66	15.5	15.3	12.7	6.4	7.7	7.5
6/5/66	15.3	15.5	14.3	11.0	13.0	12.0
6/6/66	26.7	19.2	7.4	11.0	10.5	7.2
6/8/66	14.2	15.5	12.5	8.7	8.0	6.7
6/9/66	18.2	14.3	11.7	5.5	5.5	6.7
6/13/66	15.0	13.3	13.5	7.3	7.3	8.7
6/14/66	15.6	16.3	9.3	5.7	5.3	2.2
6/15/66	14.2	14.8	10.6	5.7	5.0	4.7
6/16/66	15.3	15.3	8.0	4.7	5.7	4.2
6/19/66	17.7	17.0	15.3	12.0	13.3	
6/20/66	15.3	14.0	12.3	6.2	6.3	6.7
6/21/66	20.7	18.0	16.0	11.7	11.0	11.0
6/22/66	23.7	17.0	14.6	9.3	10.0	11.0
6/23/66	20.0	17.6	14.8	12.0	10.5	11.7
6/26/66	17.7	15.6	14.7	11.8	12.5	12.7
6/27/66	19.3	16.0	15.0	11.8	10.7	13.0
6/28/66	20.0	16.7	15.0	9.3	8.0	8.3
6/29/66	16.0	16.3	11.6	9.8	9.2	7.7
Max.	26.7	19.2	16.0	12.0	13.0	13.3
Min.	14.2	13.3	7.4	4.7	5.0	2.2
Avg.	17.8	16.0	12.7	8.9	8.8	8.5
% Reduction		10.1	28.7		1.1	4.5

Appendix II (Cont'd.)

Date	Total Phosphate PO_4 - ppm Raw	Sett	Eff	Dissolved Phosphate PO_4 - ppm Raw	Sett	Eff
7/4/66	17.8	13.7	12.5	14.0	11.2	5.8
7/6/66	27.3	24.2	13.5	16.6	15.7	12.6
7/14/66	24.1	22.2	21.7	20.3	17.4	17.4
7/21/66	25.5	17.9	12.1	12.2	11.1	10.6
7/28/66	24.2	23.5	15.5	17.8	17.8	13.5
Max.	27.3	24.2	21.7	20.3	17.8	17.4
Min.	17.8	13.7	12.1	12.2	11.1	5.8
Avg.	23.8	20.3	15.0	16.2	14.6	12.0
% Reduction		14.7	36.9		9.9	25.9
8/4/66	20.2	17.3	9.6	10.8	8.7	7.5
8/11/66	26.5	17.4	13.0	4.8	10.6	8.7
8/18/66	17.4	16.4	9.1	9.7	9.2	6.7
8/25/66	20.3	17.4	11.6	12.8	10.9	11.1
8/31/66	21.7	18.3	12.0	12.5	9.2	9.0
Max.	26.5	18.3	13.0	12.8	10.9	11.1
Min.	17.4	16.4	9.1	4.8	8.7	6.7
Avg.	21.2	17.4	11.0	10.1	9.7	8.6
% Reduction		17.9	48.2		4.0	14.9
9/8/66	26.1	21.2	15.4	12.5	10.8	12.1
9/15/66	24.6	20.7	10.1	8.2	7.7	8.9
9/22/66	37.1	26.0	6.3			
9/28/66			10.1			
9/29/66	26.7	20.7	12.4	12.2	12.4	8.8
Max.	37.1	26.0	15.4	12.5	12.4	12.1
Min.	24.6	20.7	6.3	8.2	7.7	8.8
Avg.	28.6	22.1	11.1	11.0	10.3	9.9
% Reduction		22.7	61.2		3.9	14.9
10/6/66	23.3	15.3	12.7	12.3	4.1	6.7
10/13/66	34.5	24.0	12.0	14.4	14.0	9.8
10/20/66	27.3	18.2	9.4	12.4	11.8	5.7
10/27/66	31.5	23.7	14.5	12.2	14.4	9.4
10/31/66	24.0	20.0	10.1	10.7	10.7	8.6
Max.	34.5	24.0	14.5	14.4	14.4	9.8
Min.	23.3	15.3	9.4	10.7	4.1	5.7
Avg.	28.1	20.2	11.7	12.4	11.0	8.0
% Reduction		28.1	58.4		11.3	35.5

Appendix II(Cont'd.)

Date	Total Phosphate PO_4 - ppm Raw	Sett	Eff	Dissolved Phosphate PO_4 - ppm Raw	Sett	Eff
11/4/66	19.7	14.5	10.2	11.1	8.3	8.2
11/10/66	15.7	12.4	9.6	9.4	9.9	8.2
11/16/66	23.3	22.8	14.5	13.1	12.0	7.7
11/24/66	25.2	20.3	11.4	13.3	12.5	9.6
11/30/66	20.0	18.6	10.5	10.9	10.9	8.4
Max.	25.2	22.8	14.5	13.3	12.5	9.6
Min.	15.7	12.4	9.6	9.4	8.3	7.7
Avg.	20.8	17.7	11.2	11.6	10.7	8.4
% Reduction		14.9	46.2		7.7	27.6
12/8/66	26.6	24.4	14.2	13.3	11.0	9.2
12/15/66	21.8	17.3	10.8	11.2	10.8	8.2
12/21/66	22.0	20.0	12.5	10.2	8.8	7.2
12/29/66	19.5	16.7	15.5	11.1	13.3	8.1
Max.	26.6	24.4	15.5	13.3	13.3	9.2
Min.	19.5	16.7	10.8	10.2	8.8	7.2
Avg.	22.5	19.6	13.3	11.4	11.0	8.1
% Reduction		12.9	40.9		3.5	28.9

Appendix III

Cleveland, Ohio
Easterly Water Pollution Control Center

Plant Operating Data - Activated Sludge Battery No. 3 (Tanks No. 9-12)
April 18-27, 1967

Date	Pri. Eff. Flow mgd[1]	Ret. Sludge Flow mgd	Avg. % Ret. Sludge	Avg. Air Applied CF[2]/gal PE	Range in % Ret. Sludge	Range of Pri. Eff. Flow Rate (mgd)
4/18/67	30.8	8.6	27.9	N.A.	25-35	20-35
4/19/67	29.3	8.7	29.7	N.A.	25-34	21-38
4/20/67	29.7	8.6	29.0	0.90	26-34	21-35
4/21/67	37.9	9.2	24.2	0.66	19-31	27-50
4/22/67	32.8	9.1	27.8	0.85	24-33	23-40
4/23/67	32.4	9.2	28.4	0.89	19-33	24-48
4/24/67	32.8	9.1	27.7	0.91	24-34	23-40
4/25/67	30.3	8.9	29.4	0.95	26-34	23-36
4/26/67	27.5	9.0	32.7	1.07	27-34	18-34
4/27/67	29.6	8.5	28.7	0.92	26-35	20-35

1/ Million Gallons Per Day
2/ Cubic Feet

Appendix IV

TOTAL PLATE COUNT

Suspended Solids Variation

Low Solids, April 20, 1967:

Jug No.	Aeration Time (Hrs.)			
	0 (4:00 pm)	2	4	6
1	8.4×10^5	1.1×10^6	TNTC-10^{-4}dil.	5.7×10^5
2	TNTC-10^{-4}dil.	2.1×10^6	TNTC-10^{-4}dil.	7.5×10^5
3	2.1×10^6	3.5×10^6	TNTC-10^{-4}dil.	1.4×10^6
4	1.4×10^6	TNTC-10^{-5}dil.	6.9×10^5	6.7×10^5
5	2.9×10^6	TNTC-10^{-5}dil.	3.0×10^5	overgrown
6	1.9×10^6	TNTC-10^{-4}dil.	1.4×10^6	overgrown

High Solids, April 21, 1967:

Jug No.	Aeration Time (Hrs.)	
	0 (1:30 p.m.)	5
1	3.2×10^6	TNTC at 10^{-5}dil.
2	1.7×10^6	2.1×10^6
3	3.2×10^6	2.2×10^6
4	5.5×10^6	1.2×10^5
5	1.0×10^6	7.1×10^5
6	4.1×10^6	2.9×10^6

BOD Variation

High Suspended Solids, April 24, 1967:

Aeration Time-Hrs.	Jug No. 1	Jug No. 3	Jug No. 6
0 (3:00 pm)	Contaminated	Contaminated	Contaminated
1	Contaminated	Contaminated	Contaminated
2	4.6×10^5	1.3×10^6	2.8×10^6
3	2.8×10^5	7.2×10^5	2.9×10^6
4	2.1×10^5	9.3×10^5	3.9×10^6
5	8.2×10^5	2.6×10^6	4.5×10^6
6	7.3×10^5	5.2×10^5	1.4×10^6

Low Suspended Solids, April 25, 1967:

Aeration Time-Hrs.	Jug No. 1	Jug No. 3	Jug No. 6
0 (3:00 pm)	2.7×10^5	5.0×10^5	3.8×10^6
1	1.4	2.5	2.3×10^5
2	2.0	1.9	3.3
3	3.1	1.8	2.2
4	3.2	5.5	2.5×10^6
5	6.3	1.1	2.7×10^5
6	1.7	2.3	2.4

Soluble Orthophosphate Variation
April 26, 1967

Aeration Time-Hrs.	Jug No. 1	Jug No. 3	Jug No. 4	Jug No. 5
0 (12:30 pm)	2.3×10^5	6.3×10^5	TNTC-10^{-6}dil.	TNTC-10^{-6}dil.
2	1.9	OG at 10^{-6} dil.	2.0×10^5	3.7×10^5
4	4.0	5.0×10^5	1.5×10^6	1.6×10^6
6	1.0×10^6	1.0×10^6	3.0×10^6	1.4×10^6

Chemical Addition
April 27, 1967

Aeration Time-Hrs.	Jug No. 1 (Control)	2(Al^{+3})	3 (Fe^{+3})
0 (12:00 N) Before Chem. Add.	1.2×10^6	1.8×10^6	2.0×10^6
5-min after chem. add.	-	2.9×10^5	2.7×10^5
2	3.7×10^5	4.3	6.6
4	4.4	5.6	7.9
6	2.6	2.9	3.7

Plant Characterization

Date	Tank No.	Aeration Tank ML TPC Influent	Aeration Tank ML TPC Effluent
4/18/67 5:00 pm	1	2.5×10^5	6.8×10^5
	3	5.0×10^5	4.7×10^5
	5	7.5×10^5	6.1×10^5
	7	5.7×10^5	8.2×10^5
4/26/67 3:00 pm	9	7.6×10^5	3.3×10^5

Date	Return Sludge Channel No.	TPC
4/18/67 5:30 pm	1	4.0×10^6
	2	1.8×10^6
	3	3.0×10^6
	4	2.2×10^6
4/27/67 12:30 pm	4	7.9×10^5

Date	Primary Effluent TPC
4/18/67 6:00 pm	1.3×10^5
4/27/67 12:00 N	3.1×10^5

Date	Raw Sewage TPC
4/25/67 12:30 pm	1.2×10^5
4/26/67 1:30 pm	1.8×10^5

Acclimation Study

Date	Time	TPC
4/25/67	11:30 a.m.	3.4×10^8
	9:00 p.m.	1.4×10^6
4/26/67	10:30 a.m.	2.0×10^5
	6:30 p.m.	1.6×10^6
4/27/67	11:50 a.m.	6.8×10^5
	12:15 p.m.	2.7
	2:00 p.m.	1.5×10^6
	4:00 p.m.	2.6×10^5
	6:00 p.m.	7.6×10^5

Tank-Jug Simulation
April 27, 1967

Sample	Time	TPC
Jug	2:15 p.m.	5.3×10^5
	4:15 p.m.	1.2×10^6
AT #10 3/4 pt.	4:15 p.m.	5.2×10^5

Jug Characterization
April 27, 1967

Time	TPC
12:00 N	3.1×10^5
2:00 p.m.	1.4×10^6
4:00 p.m.	2.1×10^5
6:00 p.m.	5.6×10^5

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